A PALAEOENVIRONMENTAL INTERPRETATION OF THE CRAIGHEAD INLIER AND WOODLAND POINT, (LOWER SILURIAN), GIRVAN, SOUTHWEST SCOTLAND

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DECLARATION

The research presented in this thesis has been undertaken by myself. Where used, the work of others has been stated specifically as a reference, or as an acknowledgement.

ABSTRACT

In the Girvan district Silurian (Llandovery) sediments outcrop in three areas. These are 1) the Craighead Inlier (*vesiculosus - ?sedgwickii* zone) 2) the shore exposures at Woodland Point (*cyphus - gregarius* zone) and 3) the Main Outcrop south of the Girvan Valley (*cyphus - crenulata* zone).

The sedimentary successions in the Craighead Inlier and at Woodland Point have been re-mapped and logged in detail, and formal lithostratigraphic units have been re-defined. The sedimentological characters of each of the lithostratigraphical subdivisions are here described and interpreted. Basal Silurian sediments overlie and overlap older Ordovician rocks in a southwesterly direction. In the two areas under study the sediments are largely turbidites which accumulated in separate submarine fan systems - each section is interpreted as a series of overlapping lobes in which there was both lateral and downflow transitions from conglomerates into fine sediments. Initially the provenance lay to the northwest.

In the conglomerates, data on clast shape, size, roundness and composition, are presented, as are bed thickness variations. Cyclicity within the sequence, where coarsening- and thickening-upward units alternate with thinning- and fining-upward units relate to phases of fan progradation and aggradation whereby erosional channels built out and gradually became choked when flow was diverted elsewhere.

Sediments were examined under transmitted light and also by cathodoluminescence. Texturally and chemically the sediments are immature, as is generally characteristic of lithic arenites. As with clast composition in the conglomerates there is a gradual decline in diversity of the rock fragments on ascending the sequence. Whereas the Mulloch Hill Conglomerate Formation has a very diverse clast assemblage the stratigraphically higher Upper Saugh Hill Grit Formation contains almost exclusively quartz pebbles which may record the proximal unroofing of a meta-quartzite basement which had a discontinuous cover of volcanic, low grade metamorphic and sedimentary lithologies. Preliminary cathodoluminescence studies highlight differences between the luminescence colours of apatite, which is yellow in the Mulloch Hill Conglomerate Formation, but green in the Upper Saugh Hill Grit Formation, possibly suggesting a change in provenance.

Fossils are listed and illustrated and a taxonomic review of the brachiopods of the Mulloch Hill Formation is given. Some of the brachiopods in the Craighead Inlier seem to be directly descended from those of the underlying Ordovician. As the early Silurian sea flooded the irregular - Ordovician seafloor (blocks separated by listric east-west faults) a fauna dominated by these brachiopods gradually re-colonised the substratum. Taphonomic studies reveal that the majority of fossils occur in lenses, and that the multi-element fossils are disassociated. Brachiopods are mostly disarticulated and pedicle to brachial valve ratios are uneven. In the Craighead Inlier the valves are orientated dominantly convex-up, whereas in the shore sections they are generally concave-up. It is probable that on death the fossils were locally transported and drifted along the sea floor. The *Hyattidina* and succeeding *Stricklandia/Clorinda* 'communities' are thus best regarded as associations rather than the relics of living communities. The Rough Neuk Starfish Bed, however, is an obrution deposit in which a sediment flow rapidly buried the fragile starfish and delicate crinoids, which are perfectly preserved. The palaeobiology of the constituent fossil taxa in the brachiopod - dominated associations is discussed and aftger integrating with all available data, their ecology and the environment in which they lived are summarised. Distribution of the associations is attributed to substrate availability.

The series of alternating shelly and graptolite facies correlates with the phases of progradation and aggradation of the submarine fan and may correlate with minor changes in sea level. Both the Craighead Inlier and the coastal sections derived sediment from the same broadly northerly source, though slight variations in clast composition may reflect a varied local palaeogeography.

ACKNOWLEDGEMENTS

John Donne (1624) once wrote 'No man is an island, entire of itself; every man is a piece of the Continent, part of the main'. Unfortunately it is impractical to acknowledge all of the people who have been fundamental to the completion of this thesis.

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To all the people concerned: Many Thanks.

Dedicated to Major A Ward MBE, MM and Mrs U Ward

CONTENTS

CHAPTER 1

INTRODUCTION

1.1 OBJECTIVES

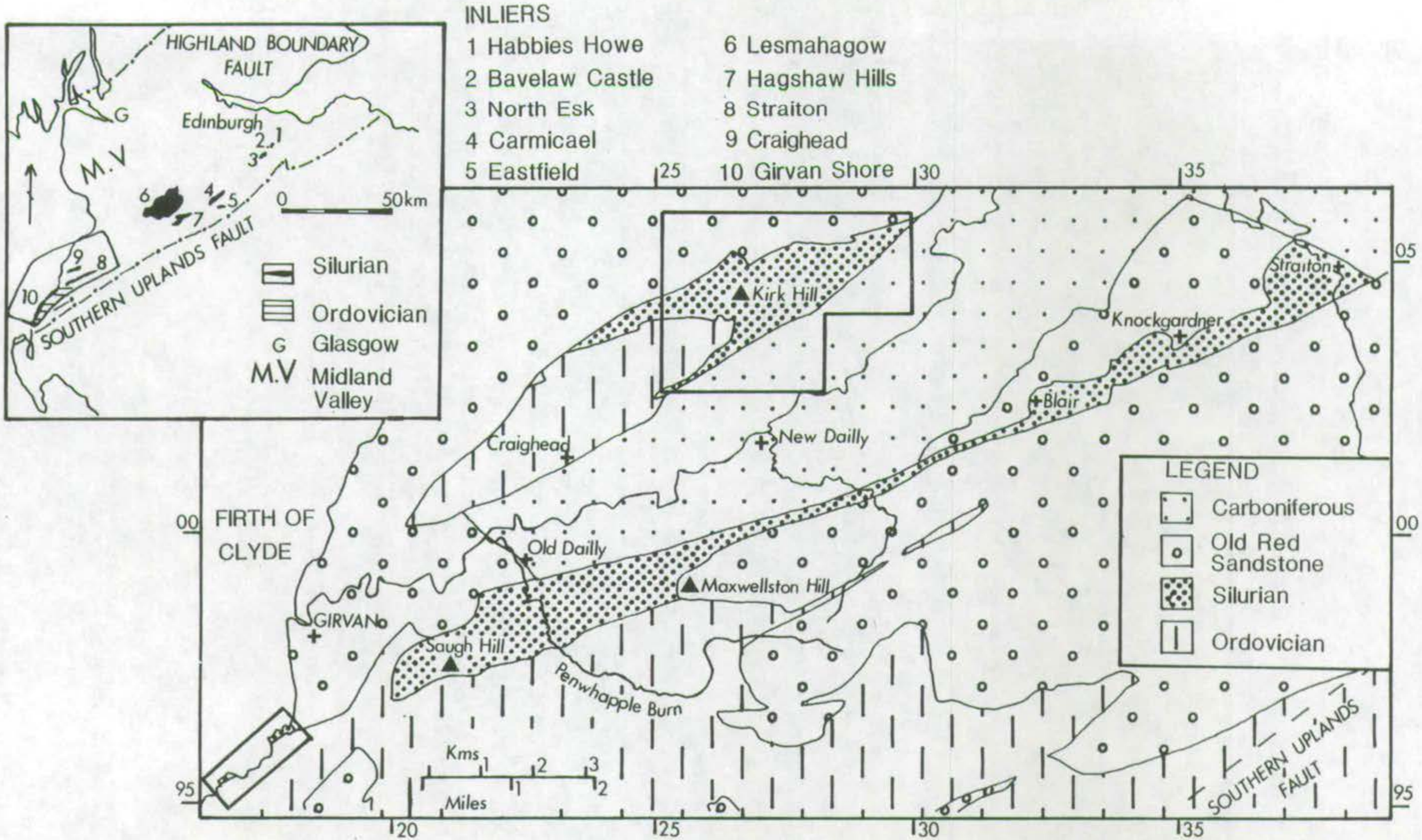
The aim of this study is the interpretation of the depositional environment of two of the three Silurian outcrops occurring in the Girvan district, namely the Craighead Inlier and the shore exposures at Woodland Point. The third area, known as the Main Outcrop, is situated south of the Girvan valley, stretching from Saugh Hill northeast to Straiton, and is being contemporaneously studied by Niall Höey (U.C., Galway).

1.1.1 Tectonic Setting

In the Midland Valley a number of small Silurian Inliers lie to the north of the Southern Upland Fault, of which the Craighead Inlier is one (Fig. 1.1). East of Girvan, the Silurian crops out at: Lesmahagow, Hagshaw Hills, Carmichael, and the North Esk, Bavelaw and Loganlee Inliers in the Pentland Hills. This chain of discontinuous Silurian outcrops extends through northern Ireland (Pomeroy, Lisbellaw, Charlestown) to South Mayo. Of the Scottish Inliers, Girvan affords the most stratigraphically complete section and incorporates the Ordovician-Silurian junction where Lower Llandovery sediments lie unconformably upon Upper Ordovician strata. In the Main Outcrop, the Silurian sequence extends into the Wenlock. The sediments in the other Inliers are entirely of Upper Llandovery and Wenlock age. Though the facies differ in the various Scottish Inliers the sediments show a gradual conformable transition from Llandovery marine turbidite sequences at the base to Wenlock and Ludlow shallow brackish or even fresh water beds (for summary see Walton, 1983).

Over many years these inliers, particularly those of the Girvan district, have generated much speculation as to their tectonic setting and consequently the study area lies in a region to which several tectonic models have been applied. It is known that these Silurian sediments accumulated on the northern margin of the Iapetus Ocean. The associated Caledonian Orogen was interpreted by Dewey (1971) as the consequence of plate interactions at a destructive margin and the Southern Uplands sequence was seen as the resulting accretionary prism (McKerrow et al., 1977).

The Southern Uplands are truncated by a number of strike faults which are thought to be rotated reverse faults (Fyfe and Weir, 1976; McKerrow et al., 1977; Weir, 1979; Cook and Weir, 1979). These divide the Southern Uplands into a number of tracts. Walton (1983) has recognised six tracts whilst Leggett et al. (1979a) have recognised ten. The application of the accretionary prism model to the Southern Uplands, still stimulates controversy as indicated by McKerrow's (1987) recent review of the divergent opinions



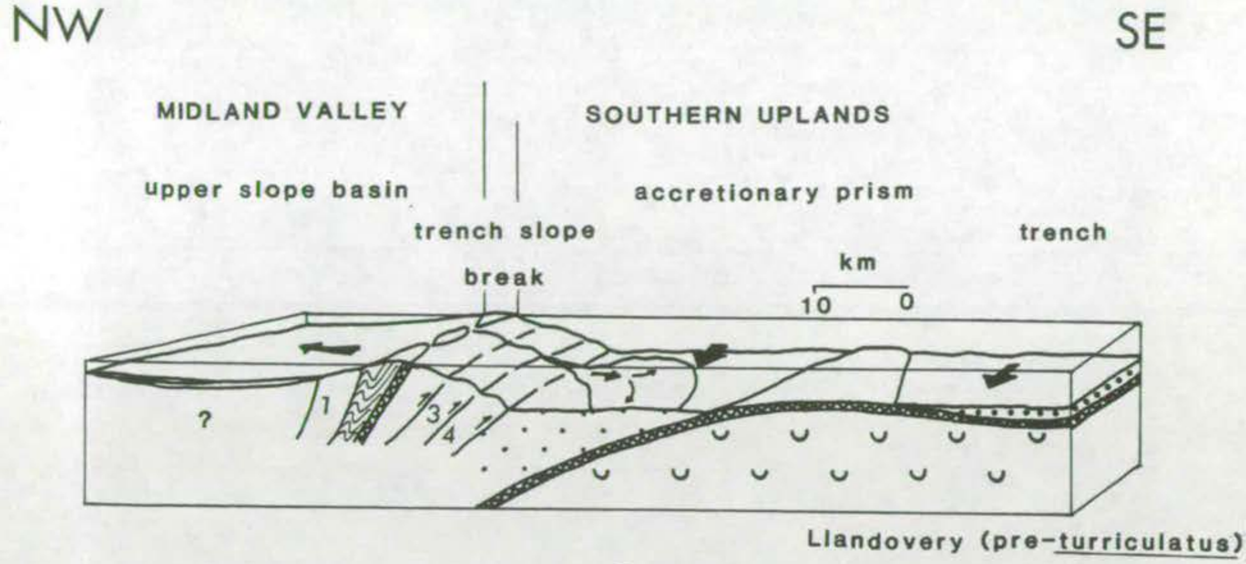
Fig(1.1) Location map and outline geology of the Girvan District,showing the areas studied.

and accompanying series of papers written by established workers. The accretionary prism model is based upon: 1) the association of oceanic sediments e.g. turbidites and black shales, 2) the opposite directions of younging between and within the tracts, 3) the fact that the direction of tract younging coincides with the direction of progressive younging in the base of the Ordovician greywacke pile and 4) the possible increase in metamorphic grade towards the north west (McKerrow et al., 1977; Legett et al., 1979; Gales, 1979; Leggett, 1980; Leggett et al., 1982).

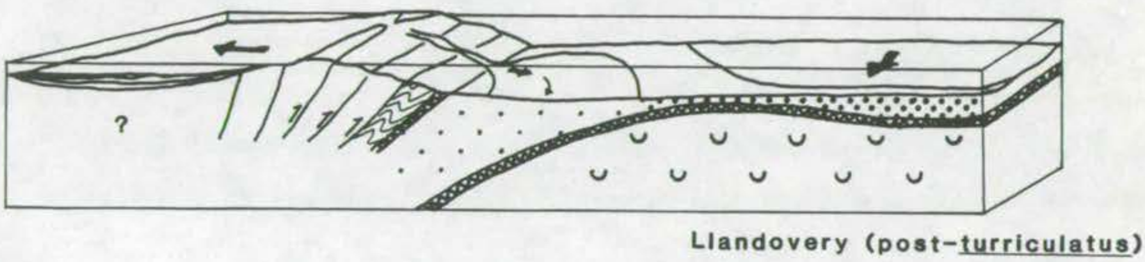
One school of thought led by Legget advocates a model in which the Midland Valley represents a fore-arc basin, separating a trench accretionary prism to the south from a volcanic arc terrain to the north (in Aberdeenshire) (Fig. 1.2). The detritus which accumulated in the Southern Uplands trench was possibly derived from the erosion of the uplifting Dalradian terrain (Yardley et al., 1982).

Bluck, however, interprets the Girvan sequence as representing a proximal fore-arc basin, the Southern Uplands rocks as a trench, and the Midland Valley floor as an arc supplying detritus to the basin in the south. Consequently, part of the forearc basin is missing and it is thought that the Southern Uplands accretionary prism has thrust over the basin (Bluck 1983, 1985) (Fig. 1.3). Recently Bluck (1985) and others have recognised massive strike-slip movements along the major faults. On the basis of matching granite boulders, occurring in the Ordovician and Silurian conglomerates of the Southern Uplands with those of Newfoundland, Elders (1987) suggests a total lateral displacement of 1500km occurring between the Caradoc and the early Devonian. This gives rise to the question; are the Craighead, Main Outcrop and Coastal outcrops in situ or have they been juxtaposed as a consequence of strike-slip discpacement? A more detailed discussion of the tectonic setting will be given in Chapter 10.

The Girvan district is thus of particular interest because of its tectonic implications: 1) the study area lies in a Palaeo-fore-arc basin, 2) to the north of this lay an arc and 3) sediment transport direction may have been variable (NW-SE). Most of the previous research work in the Craighead Inlier has concentrated on documenting the fauna and producing detailed palaeontological monographs which are of great value to taxonomic studies but, by comparison, the sedimentology has been rather neglected. It is vital that both the geological disciplines of palaeontology and sedimentology should be carefully studied and used in conjunction, not only for palaeoecological studies but also so that their information can be synthesised in order to attain a depositional setting model. This may partially help in elucidating the controversy concerning the general



Fig(1.2) Schematic block-diagrams across the fore-arc of the Northern Iapetus margin in the southern Scotland,in Lower Palaeozoic times.Taken from Leggett (1980).



Trench wedge facies

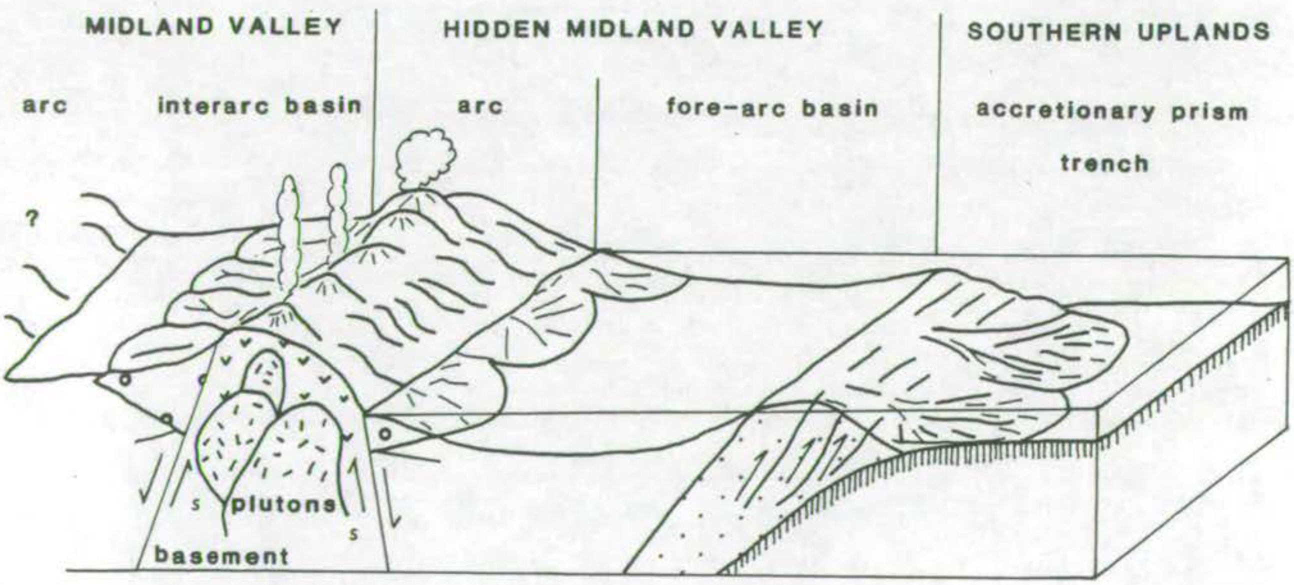
Pelagic plate facies

Terrigenous plate facies

Ocean crust /ophiolite

Arrows represent sediment dispersal directions

FIGURE 1.3



Fig(1.3) Bluck's (1983) interpretation of the Midland Valley during Lower Palaeozoic times,showing an interarc basin,missing fore-arc basin and Southern Uplands accretionary prism.

regional setting of the Girvan sequence and relationship to the other Midland Valley Inliers.

1.1.2 Location

The Craighead Inlier forms a tract of hilly and partially forested ground situated approximately 6km to the northeast of Girvan, near Wallacetown and is bounded by the Grid References NS2603, NS2606, NS3003 and NS3006 of sheet 76, Kyle and Carrick District (Fig. 1.1). The Inlier is approximately 8.5km^2 comprising of low undulating hills, namely the Quarrel, Craigen, Kirk and Glenshalloch Hills, which are generally less than 249m high. The main source of income to the East Thraive High Mains and Newlands Farms is arable farming, with grassland covering most of the ground, and subsequently exposures are few. There are a number of Carboniferous coal seams underlying the Mossgennoch Woods and Glenshalloch Woods. The first mine, the Romily shaft, was opened in the early 1880s, mining steam coal. At first the coal was mined towards the east but due to numerous faults displacing seams up to 23m, and hazardous fires, the mine was worked towards the west up into Mossgennoch Wood. In the Glenshalloch Wood there is a very large disused open cast mine. The mine above Wallacetown was finally closed in 1973.

The second study area, comprising of the rocky seashore outcrops of Woodland Point and the Haven (NS1796 and NS1795 respectively), lies approximately 3km south of Girvan and can be reached by taking the A77 (T/road). Less than 1km^2, the outcrops form jagged low topographic bosses.

1.1.3 Techniques of Study

Although the Craighead Inlier has been previously mapped by Lapworth (1882), by the Survey officers (1899) and more recently by Freshney and Floyd (1959) whose map was adopted by Cocks and Toghill (1973), it was necessary as part of the study to remap the Silurian of the two areas on a scale of 1:10,000.

Aerial photographs were studied on the scale 1:10,000 giving a general indication of exposure and topography prior to afforestation as well as important information on fault locations and trends, and glacial features. Unfortunately, due to the lack of exposures, a number of trenches had to be excavated, particularly in the case of the Ordovician-Silurian boundary. In order to resolve the problems affecting lithostratigraphy and local correlation, some of the formational names were revised. Field data was collected and detailed measured section logs were produced and described. Measurements of clast size, roundness and sphericity in the conglomerates were calculated for textural studies. The study was initiated to give a more quantative perspective to field observations, but whilst carrying out the studies a number of difficulties arose. For example, the hardness of the matrix varies in the conglomerates, inhibiting the extraction of the clasts, and the extent of exposure varied also. Thus methods adopted for each individual conglomerate differed according to these restrictions. When studying the Mulloch Hill Conglomerate (Craighead), it was possible to extract 15 clasts using a rigid quadrat square, whose dimensions were (approximately) 20 x 20cm, every 50cm intervals. Owing to the extensive exposure of the Craigskelly Conglomerate, measurements of clasts from the Craigskelly Conglomerate Formation and Haven Conglomerate (Girvan shore) were taken from every conglomeratic bed. Due to the hardness of the matrix, clasts were unable to be extracted, and therefore clasts were measured in the field. Sphericity and roundness were estimated visually using Pettijohn et al. (1973) chart. Visual estimations were opted for, rather than numerical determinations of angularity because of the great number of factors influencing clast shape, such as composition and size. After the study had been completed it became clear that as a result of using inconsistent methods for each individual unit, the results of the study would really only give a qualitative perspective to field observations.

Sedimentary structures were observed, recorded, measured in the field and analysed in the laboratory. As a consequence of the lack of suitable lineations for palaeocurrent measurements such data are scarce, but were still synthesised in the discussion of the conditions and settings of deposition of sediments.

Complementary laboratory work on sediments in the form of thin section petrographic studies and examination of sliced slabs of rock was undertaken. Slabs of rock were oiled and polished in order to observe internal structures and in suitable cases, slabs were stained using a procedure adopted by Dickson (1965) from which acetate peels were made. Detailed petrographic descriptions were made of each Formation and point counts of 300 grains were calculated for the coarsest sediments. In addition carbonate rich thin sections were also stained using the same procedure as stated above.

Cathodoluminescence techniques had not previously been applied to the sediments of the Girvan district. Thus preliminary cathodoluminescence (CL) microscopy studies were made of the sediments from the Craighead and Coastal sections. This technique enhances both the quality and quantity of information derived from thin sections.

Since it is important to have as complete as possible a picture of the depositional setting the palaeontology of the various formations was investigated closely. Figures, descriptions, faunal lists and stratigraphic distribution tables were composed for palaeoecological studies and designations of fossil assemblages.

Fossils were collected from each locality. They were identified and where problems arose, advice was sought from specialists. Latex replicas were made, especially of brachiopods and crinoids, both of external and internal moulds. The specimens and latex were dusted with ammonium chloride using a pipette and then photographed. Graptolites were photographed by emmersing the specimens in ethanol in a shallow container.

To determine whether or not the fossils had been transported and consequently to what extent the original palaeocommunities may have been modified, if at all, the ratios of pedicle to brachial valve and the orientations of some of the disarticulated valves were calculated. This was supplemented by measurements of height, width and thickness of some brachiopods.

Where present, ostracods were extracted using a vibro-tool and fixed on to a circular SEM stub. These specimens were coated with gold and then examined under a scanning electron microscope.

The palaeontological work was supplemented with specimens from museum collections. Furthermore the sediments and fossils of the Main Outcrop of the Girvan district, particularly Penwhapple Burn and other Midland Valley Inliers and the Irish equivalents were observed on field trips for the purpose of local and regional correlations.

1.1.4 Outline of Thesis

Within the thesis there are 10 Chapters. This introductory chapter describes the general geology of the Craighead Inlier and coastal sections, presenting also a brief historical review of past research work. In Chapters 2 and 3, the stratigraphic framework, including sedimentology and palaeontology are outlined for the Craighead Inlier and Coastal Section respectively. Detailed studies of the various conglomerates, including size and roundness and sphericity are dealt with in Chapter 4. Descriptions of the petrology are given in Chapters 5 and 6, supplemented by cathodoluminescence. The biostratigraphy of the Craighead Inlier and Coastal sections are described and discussed in Chapter 7, accompanied by a more detailed study of the brachiopods present in the Mulloch Hill Formation in Chapter 8. Summaries of the palaeobiology of the fossil assemblages are given in Chapter 9. Finally Chapter 10 represents a synthesis of the sedimentological and palaeontological findings discussed previously, attempting a palaeoenvironmental reconstruction and a discussion of the tectonic setting of the Girvan district.

The appendix consists of four parts: the first contains precise definitions of the stratigraphic units, and in the second and third appendix the raw data is presented, for the sedimentology and palaeontology, respectively. Finally, in the fourth appendix, graphs are presented showing size distributions of brachiopods in the Mulloch Hill Formation.

1.2 SUMMARY OF THE ORDOVICIAN SUCCESSION

1.2.1 Girvan district

A review of the geology of the underlying Ordovician sequence of the Girvan district is given in order to outline the general depositional environment prior to the commencement of the Silurian. The Ordovician sediments of the Girvan district overlie and are thought to overstep on to the Ballantrae complex (Williams, 1962). The sediments of the Barr Group, comprising of the Kirkland Conglomerate, Stinchar Limestone and Benan Conglomerate, outcrop as: 1) a fault slice in the Stinchar Valley, 2) a strip around Aldons Hill westwards to Knockbain [NS163900], 3) a tract from Kennedy's Pass to Byne Hill and 4) at the eastern edge of the map from Laggan Hill [NS202948] south to Laigh Letterpin [NS202927]. Originally the strata were dated as Caradoc (Williams, 1962) but a subsequent revision of Ordovician biostratigraphy tends to favour a Llanvirn-Caradoc age (Ingham, 1978).

Lapworth (1882) erected the general stratigraphy for the Ordovician of the Girvan district and this was slightly modified later by Peach and Horne (1899) and more substantially by Williams (1962). In agreement with Kuenen (1953), Williams considered that the Benan and Kirkland Conglomerates were emplaced by a series of submarine slides accumulating against submarine fault scarps. In 1969, Bluck questioned this deep water depositional setting pointing out similarities between certain units (namely the *Confinis* flags and the Stinchar Limestone) within the Group, with gravels deposited in fluvial environments. Subsequently Anderton et al. (1979) queried the shallow marine depositional model for the Stinchar Limestone.

The most recent depositional model for these sediments is provided by Ince (1984) who envisages fan deltas (of the Barr Group) situated on the northern margin of the Iapetus, during the Llanvirn to Llandeilo series of the Ordovician. These fans were at least partially subaerial and prograded southwards, from a southwest-northeast trending fault delineated basin margin, across a narrow shelf.

Matrix-rich gravels, forming the top-most horizons of the units, forming subaqueous channels, are interpreted as recording the transgression and eventual abandonment of the fan delta system, whilst the intervening Stinchar Limestone represents a shallow marine fan delta abandonment facies (Ince, 1984). This was followed in the upper Llandeilo by a phase of rapid subsidence correlating with the transgression due to the presence of resedimented gravels in the lower horizons of the succeeding Benan Conglomerate. Ince postulated that the source area was uplifted as a result of granite plutons accounting for the rapid subsidence of the basinal area. The gradual reduction in subsidence rates along the basin margin faults led to fan delta progradation, as recorded by braided fluvial deposits and shallow marine carbonates.

Stratigraphically higher, the Ardmillan Group (namely the Balclatchie, Ardwell, Whitehouse and Shalloch Formations) consists mainly of turbiditic sandstones, siltstones and mudstones with conglomerates prominent in the basal part of the sequence. Sedimentological evidence suggests that the sediments were deposited from low- and high-density turbidity currents in a submarine fan environment (Cameron et al., 1986).

The lower Whitehouse Group traces a transgression from proximal calcareous flysch, containing transported shelly and trilobite fauna through the more distal unfossiliferous sandstones to thick graptolite bearing shales (Ingham, 1978). Both the Whitehouse Group and the Shalloch Formation show evidence of instability, turbulence, and downslope movement of the sediments associated with turbidity currents and sediment flows. Harper (1979, 1984) has recorded a *Foliomena* fauna from the red mudstone member of the Myoch Formation, in the upper part of the Whitehouse Group. All the known occurrences of *Foliomena* are in fine-grained rocks, usually fine mudstones, forming low density assemblages and are very sparsely distributed (Cocks & Rong, 1988). Agreeing with previous workers (for example Sheehan, 1973; Harper, 1980), that the fauna was deposited in the deep sea, Cocks and Rong point out that the fauna does not necessarily have to be ocean-facing and marginal to continents. As a consequence of changing bottom conditions and periodic disturbance by turbidites, the faunal composition may have been subjected to slight modifications. Furthermore this association was interrupted by sudden influxes of different upper slope and shelf faunas (Harper, 1979).

1.2.2 Craighead Inlier

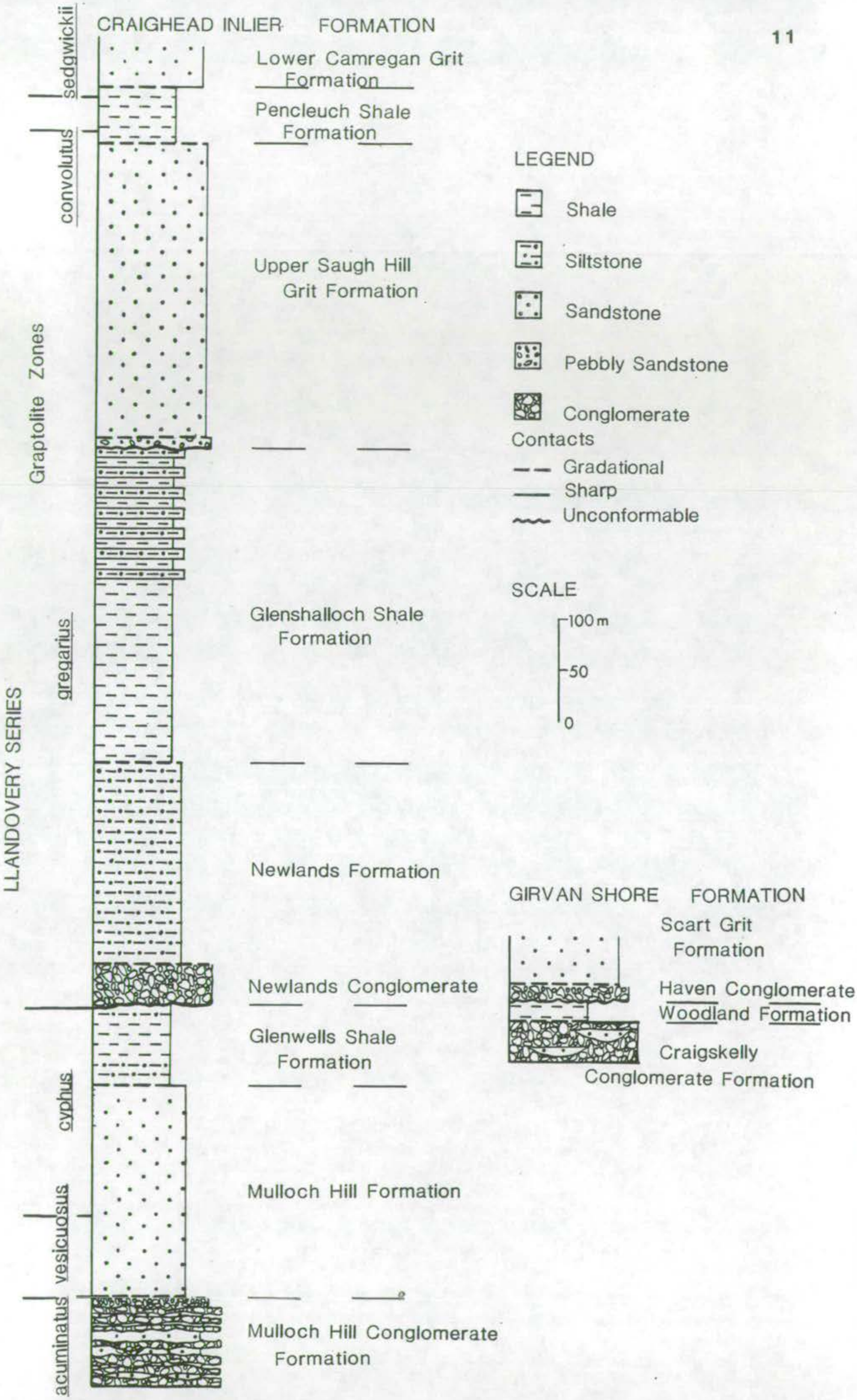
In the Craighead Inlier the characteristics of the sediments and fauna of the overlying Drummuck Group indicate an inner fan environment (Harper, 1982). Harper demonstrated that a *Christiania-Leptaena* Association possibly established itself on the proximal flanks of the fan, but its composition was locally effected by periodic overwash from the fan and mud flows along the edges. A period of intense instability is envisaged during the early Drummuck times (Harper, 1982) indicated by massive unfossiliferous silty mudstones which inhibited the local development of shelly benthos, but by the late Drummuck stability had returned. The appearance of two different faunal associations in the High Mains Formation, which are both considered to be *Hirnantia* faunas suggests a gradual regression commencing and continuing throughout the Hirnantian stage.

1.3 SUMMARY OF THE SILURIAN SUCCESSION

1.3.1 Craighead Inlier

The area studied consists of an assemblage of sediments of Lower Llandovery (Silurian) age. According to Cocks and Toghill (1973) who erected the most recent stratigraphy (modified herein) all the Llandovery zones from *cyphus* to *crenulata* inclusive are represented by graptolite faunas.

The base of the Silurian is represented by the Mulloch Hill Conglomerate Formation which is seen to overstep and overlie older Ordovician sediments in a southwesterly direction. It is comprised of three members; a lower poorly-sorted cobble conglomerate, interbedded with coarse-grained sandstone lenses, a middle thinly-bedded sandstone and an upper poorly-sorted pebble conglomerate (Fig. 1.4). It is succeeded by the highly fossiliferous Mulloch Hill Formation in which medium- to fine-grained sandstones alternate with siltstones, and towards the top of the Formation, greenish paper shales are developed. The increasing shale sandstone ratio culminates in the Glenwells Shale Formation where bioclastic siltstones grade up into blue-grey concretionary mudstones, occasionally yielding graptolites. Together the Mulloch Hill Conglomerate, Mulloch Hill, and Glenwells Shale Formations constitute the Mulloch Hill Group. The base of the Newlands Formation is marked by a locally developed quartz conglomerate (referred to here as the Newlands Conglomerate Member - the basal member of the Newlands Formation, see appendix 1) passing into a green igneous conglomerate and thickly-bedded bioclastic, bioturbated siltstones and fine-grained sandstones. Immediately overlying the Newlands Formation is the Glenshalloch Shale Formation comprising a lower unfossiliferous blue shale, a middle laminated banded shale yielding abundant organic remains of graptolites and an upper unit of shales interbedded with fine-grained siltstones. The base of the Upper Saugh Hill Grit Formation is represented by a basal pebbly sandstone and the rest of the Formation is characterised by thickly-bedded coarse-grained sandstones. The overlying greyish-brown shales and mudstones of the Pencleuch Shale Formation, yielding a rich graptolite fauna, are juxtaposed with the Lower Camregan Grit Formation - a coarse-grained thickly-bedded bioclastic purple coloured sandstone.



CRAIGHEAD INLIER
FORMATION
Lower Camregan Grit Formation
Pencleuch Shale Formation
Upper Saugh Hill Grit Formation
Glenshalloch Shale Formation
Newlands Formation
Newlands Conglomerate
Glenwells Shale Formation
Mulloch Hill Formation
Mulloch Hill Conglomerate Formation
LLANDOVERY SERIES
Graptolite Zones
sedgwickii
convolutus
gregarius
cyphus
vesicuosus
acuminatus
LEGEND
Shale
Siltstone
Sandstone
Pebbly Sandstone
Conglomerate
Contacts
Gradational
Sharp
Unconformable
SCALE
100 m
50
0
GIRVAN SHORE
FORMATION
Scart Grit Formation
Haven Conglomerate
Woodland Formation
Craigskelly Conglomerate Formation

1.3.2 Coastal Exposures

On the coast the base of the Silurian is represented by the poorly-sorted Craigskelly Conglomerate Formation (Fig. 1.4) which thins to the southwest. Coarse green-coloured sandstone lenses can be interbedded with the conglomerates. The overlying Woodland Formation, one of the richest localities in the British Silurian, yielding an abundant and diverse fossil assemblage, is characterised by massive flags passing upwards into graptolite-bearing shales. A basal quartz conglomerate, the Haven Conglomerate Member marks the base of the Scart Grits, developing into an igneous-clast rich conglomerate with the uppermost member consisting of coarse-grained sandstones.

Originally this sequence was interpreted by Cocks and Toghill (1973) and Bluck (1983) as the product of turbidite sedimentation. The base of the Silurian represents a short regression, at the beginning of the Llandovery. However this process was quickly reversed to a marine transgression where sediments were deposited along the northern margin of the Iapetus Ocean, to the south of which lay an active subduction trench (McKerrow et al., 1977).

1.4 PREVIOUS RESEARCH

1.4.1 Introduction

The earliest studies of the British Lower Palaeozoic were initiated in the 1830s, of which most was confined to Wales and the Welsh Borderland. The very rich faunas of the Girvan district soon attracted the attention of palaeontologists such as Nicholson and Etheridge, and later Wheelton Hind and Cowper Reed who produced beautifully illustrated monographs, and vigorous amateurs such as Mrs and the Misses Gray of Glasgow, John Smith of Dalry and James L Begg of Glasgow. At first progress was slightly hindered by the confusion and mistakes arising from museum palaeontologists, Reed in particular examining specimens without having visited the collection sites. Although possessing excellent specimens, they were unable to observe at first hand the fossil distributions, associations and diversity at the localities.

1.4.2 Structure and Nomenclatures

Following the less-detailed work of Sedgwick in 1850, Murchison (1851) produced a very descriptive account of the fossiliferous succession at Girvan. The ascending series he distinguished consisted of: 1) lavas, 2) Craighead Limestone, 3) the conglomerates of the Mulloch Hill and 4) the Drummuck Shales. His work was further expanded upon by Miller (1858). It was not until Geikie (1869) wrote a summary of the stratigraphy of the area that the age and stratigraphic order of the beds was settled.

Having established a zonal sequence of graptolites in the Moffat area in 1878, Lapworth applied his graptolitic scheme to the Girvan succession. His classic paper of 1882, illustrated with a large-scale detailed map, provided an excellent stratigraphic framework upon which subsequent workers have based their work. In it, Lapworth recognised: 'grandest palaeontological break in the entire Girvan succession' (1882) between the top of his Ardmillan Series (the Lady Burn Mudstones) and the base of the Newlands Series (the Mulloch Hill Conglomerate). This apparent hiatus was confirmed later by the work of Peach and Horne (1899), commissioned by the Geological Survey to revise his work and their findings also closely adhere to Lapworth's account. None of these authors, however, found the High Mains Sandstone Formation, overlying the Lady Burn Mudstones, which actually represents the top of the Drummuck Formation and the Ordovician.

After a lull of approximately thirty-six years, when little research was undertaken, interest was resurrected when Lamont (1935), whilst studying the Ashgill (Ordovician) of the Craighead Inlier defined the High Mains Formation. He added the High Mains Sandstone Formation (occurring near the High Mains Farm) to the base of the Mulloch Hill Group, thus assigning to it an early Llandovery age. Confusion arose as Lapworth (p618) had originally made one reference to the High Mains beds which he had designated as sandstones overlying the Mulloch Hill Conglomerate. Thereafter the reference was not repeated again in the text. Neither Peach and Horne nor Lamont mention this. Although Lapworth had made this reference to the High Mains Sandstone above the Mulloch Hill Conglomerate, he did include the High Mains Sandstone with that of his *Trinucleus* Shale (the Drummuck Group) and considered the Mulloch Hill Conglomerate Formation to directly succeed the Beds of the Drummuck Group. Therefore Lapworth regarded the base of the conglomerate as representing an unconformity.

However Lamont presumed that the High Mains Sandstone represented the base of the Silurian because he believed that its fauna was similar to that of the Mulloch Hill Group with its abundant fauna of *Meristella* sp. He did also recognise that '*Orthis sagittifera*', (McCoy) was a characteristic faunal element, but this is generally unknown in the main part of the Mulloch Hill Group. He cited further evidence from an outcrop in an old quarry where slabby sandstones dipped approximately 30° under the Mulloch Hill Conglomerate whilst the nearest exposure of Drummuck strata consisted of fine splintery mudstone. The absence of the sandier and more-massive upper Drummuck, apparently indicated an unconformity, leading Lamont to interpret the High Mains indicated an unconformity, leading Lamont to interpret the High Mains Sandstone as representing the first stage of a transgression in the Mulloch Hill times. Since he was unable to find a suitable topographic name, this sandstone occurring below the conglomerate was called the High Mains Sandstones (Harper, 1981).

After describing the trilobite *Flexicalymene scotica*, from the High Mains Sandstones, and recognising that the brachiopod *Hirnantia sagittifera* is a form characteristic of the top part of the Ashgill Series, Lamont (1949) realised that he had made an error over the age and subsequently advocated a Hirnantian age (Ashgill Series) for the High Mains Sandstones, and proposed that the Mulloch Hill Conglomerate should represent the base of the Silurian. Later in 1970, Ingham and Wright's recognition of elements of a *Hirnantia* fauna support this.

Perhaps one of the most important advancements in the general stratigraphy of the Craighead Inlier was made by Freshney (1959). Firstly he demonstrated that the Inlier extended much further northeastwards, into what had previously been presumed by Lapworth and Lamont to be the Old Red Sandstone. The thick quartz pebble sandstone, formerly mapped as Old Red Sandstone was shown to be similar in both lithology and stratigraphic position to the Saugh Hill Grits, at its type locality on the other side of the Girvan Valley. Overlying the Saugh Hill Grits, a further two formations, namely the *Monograptus sedgwicki* Shales and Camregan Grits, were added to the top of the stratigraphical column. These formational names were transferred from the Main Outcrop. As a consequence the estimated thickness of the sediments in Craighead increased dramatically from 3650' (1112m) - an estimate given by Lapworth (1882) - to an approximate thickness of the Silurian sediments in the Craighead Inlier of nearly 3,000m (Cocks & Toghill, 1973).

In contrast to the older interpretation in which the boundary between the Silurian and Old Red Sandstone was represented by a fault, Freshney showed that in the north the Silurian sediments are in fact overstepped by an unconformity at the base of the Old Red Sandstone. Above the Glenshalloch Wood, a locality was referred to by Freshney (1959) where this unconformable relationship could be seen. There the basal Old Red Sandstone conglomerate contains fragments of fossiliferous Newlands Formation, overlying the Saugh Hill Grits.

Another unconformity was postulated at the base of the Newlands Formation, where the Newlands Formation overstepped the Glenwells Shale onto the Mulloch Hill Formation in the vicinity of Mulloch Hill. Freshney pointed out that in two other sections in the Girvan area, the Newlands beds were mapped as faulted against the Pre-Drummuck Group, with the Mulloch Hill Group being absent. Either a fault exists with a large displacement of 3,000-4,000' (914-1219m) or, more likely, a large portion of the succession is absent beneath the Newlands Beds. This was thought to account for the overall coarse grain size, and basal conglomeratic characteristics of the Newlands Formation, and was supported by the brachiopod fauna (which suggest correlation with B_1 and possibly B_2 of the Llandoverian, at Llandovery (Jones, 1925; 1949; Williams, 1951)). Thus there is a stratigraphical break beneath B_1.

Freshney partly based his argument upon Lapworth's correlation of the Newlands Formation with Woodland Formation at the coast, and the base of the Tralorg Formation of the Main Outcrop. The similarity of the basement beds of the quartz conglomerate of the Scart Grits, together with the general correspondence in petrological character, led Lapworth (1882) to assume that the strata at the coast belonged to the same group as the Newlands and Glenshalloch beds of the Craighead Inlier. Lapworth correlated the striped shales of the Woodland Formation to the zone of striped shales in the neighbourhood of Penwhapple since the strata were apparently lithologically similar but also because the fossils were apparently identical in the two localities. On the northwestern flank of Saugh Hill a boulder conglomerate (thought to be identical with that of the Craigskelly) rests upon the Barren Flagstones of Cuddystone Burn and similarly southeast of the Horse Rock (on the coast), the Craigskelly Conglomerate lies unconformably upon the top of the Barren flagstones and shales. Lapworth's assumption of an unconformity at the base of the Craigskelly Conglomerate would avoid the presence of the Drummuck and Mulloch Hill Formations south of the Girvan valley, thus reducing the postulated downthrow of the Saugh Hill and Woodland Faults to comparative insignificance. Lapworth believed that the quartz conglomerate of the Scart Grits could be correlated with a band found at the base of the Saugh Hill Rocks at Saugh Hill Burn and that the bedded gritstones on the coast, which are weathered to a yellow-pink tint, were also thought to be characteristic of the Saugh Hill Group of the Main Outcrop.

Cocks and Toghill (1973), who have provided the most recent biostratigraphical account, argue against the existence of an unconformity at the base of the Newlands Formation. Instead they correlate the Woodland Formation with the Tralorg Formation (of the Main Outcrop) and the Glenwells Shale, establishing a Rhuddanian (*cyphus* zone) age on the bases of the graptolite fauna. Furthermore they give measurements of the strike of the Newlands Formation which generally agree with underlying beds eliminating the possibility of an angular unconformity at the base of the Newlands. The local variation in direction of the beds is attributed to recent glacial drag. Due to the contrast in lithologies, with the conglomerate at the base of the Newlands Formation appearing quite different to the Newlands buff-coloured sandstones and calcereous siltstones, Cocks and Toghill (1973) identified a new mappable unit referred to as the

Glenwells Conglomerate. Whilst not retaining the useful major Group names introduced by Lapworth such as Mulloch Hill Group, Saugh Hill Group, Cocks & Toghill created a number of new formational names.

Unlike Lapworth, who only recognised an unconformity at the Haven (Shalloch Forge), Cocks and Toghill believe that the Ordovician-Silurian junction at the Main Outcrop and coastal sections are not separated by a major fault (the Saugh Hill Fault as advocated by Lapworth), but in fact the base of the Silurian is represented by an unconformity throughout the whole Girvan area.

In their biostratigraphic account Cocks and Toghill point out that out of the twenty-three named formations in the Girvan district, fourteen have graptolites while only seven have shelly faunas - the upper part of the succession is almost exclusively turbiditic and rich in graptolite faunas. They closely documented the faunal characteristics and applied the community depth-related concept established by Ziegler et al. (1968) in the Welsh Borderlands, reportedly recognising a number of changes in the composition of the fossil community associated with a change in depth.

1.4.3 Palaeontology

Due to the abundance and excellent preservation of fossils in the Girvan district, notably the Woodland Formation yielding the only middle Llandovery shelly fauna in Scotland, much work has concentrated on the individual fossil groups. Perhaps the most significant contribution to amassing palaeontological material from the Girvan district was made by Mrs and Miss Gray. Upon the death of her husband, Robert Gray, a Glasgow banker who made frequent trips to Girvan to collect fossils, Mrs Gray and her four daughters, searched for the next 50 years, every part of the lower Palaeozoic strata of Girvan, yielding a vast quantity of invaluable fossils which they sent across Great Britain to all the major museums. She provided the fossils for many great palaeontologists, including F R Cowper Reed of Cambridge and Etheridge and Nicholson. Apparently Reed was not a keen field geologist, prefering to stay in the warmth of a Cambridge laboratory, describing and illustrating the Girvan fossils. It was not until later in his life that he actually visited Scotland.

The first major monograph devoted entirely to the Girvan fossils was published by Nicholson and Etheridge (1878-1880) which includes trilobites, echinoderms and ostracods. Brachiopod research work has included Davidson (1866-71, 1882-83), Reed (1917, 1935, 1944), Lamont (1934) and Begg (1946a). A wealth of literature exists on the trilobite fauna with contributions by Reed (1903-35, 1941), Begg (1940, 1943, 1944, 1950), Wood (1933), Begg & Reed (1944), Shirley (1936), Whittington (1950, 1956), Tripp (1958), Lane (1971), Owens (1973), Hughes, Ingham & Addison (1975), Howells (1982).

The molluscs are also fairly well documented; Bivalves are described by Hind (1910), Reed (1941, 1946), Lamont (1946a); Gastropods Reed (1910, 1940), Longstaff (1902, 1906, 1924), Lamont (1946b) and Peel (1975). Graptolites have been documented by Elles & Wood (1901-1918).

The abundant crinoid fauna has received little attention - only Spencer (1914-65) and Begg (1934) described some of the taxa. Minor elements of the fauna have been described by Blake (1882) on the cephalopods, Slater (1907), Begg (1946b) on the conularrids and Reed (1908) on the receptaculitids.

1.4.4 Age and Correlation

Early opinions regarding the age of the Silurian rocks were relatively imprecise whereas subsequent work has proved that all stages of the Llandovery are presumed in the succession at the Craighead Inlier. Utilising the rich graptolite fauna, Lapworth (1882) first suggested the possibility of a Llandovery age, for the succession. He gave an *acuminatus* age for the Glenwells Shale and a *gregarius* age for the Glenshalloch Shale (which he thought represented the top of the succession in the Inlier). Lapworth's conclusion that the Glenwells Shale had an *acuminatus* zone age was based upon a single specimen of *Akidograptus acuminatus*. This specimen is now preserved at Birmingham University (BU 306a) and has been re-identified as *Orthograptus* sp. (Cocks & Toghill, 1973). Identical graptolites of the upper *cyphus* zone occur in the Woodland Formation (coast) and Tralorg Formation (Main Outcrop) indicating an upper *cyphus* zone age for the Glenwells Shale. Lapworth also assumed that the Craigskelly Conglomerate and overlying strata were stratigraphically higher than the Glenwells Shale of the Craighead Inlier - that they yielded an *acuminatus* zone and in so doing correlated the Woodland Formation with the Newlands Formation.

Freshney (1959) used a combination of brachiopod and graptolite zonal schemes, recognising an *acuminatus* age for the Mulloch Hill Formation, characterised by brachiopods typical of A_2 and A_3 of the Llandoverian, at Llandovery (Jones, 1925, 1949; Williams, 1951) thus placing the Glenwells Shale at about the *vesiculosus* zone. The succeeding Newlands and Glenshaloch Shale correlate with the ages originally designated by Lapworth. He was able to correlate the shales (Pencleuch Shales) yielding *Petalograptus polmeus* with the shales occurring on the southeast of the Valley characterised by *Monograptus sedgwicki* and correlating with C1 at Llandovery. The Lower Camregan Grits were dated with the aid of brachiopods - the most dominant being referable to a variety of *Pentamerus laevis* (J. de C. Sowerby) which is characteristic of the basal Upper Llandovery of the Oslo region (St. Joseph, 1938).

Freshney's biostratigraphy was later revised by Cocks and Toghill (1973). Although the exact age of the Mulloch Hill Conglomerate is uncertain, it is estimated as being approximate to the middle of the Rhuddanian stage, whilst the Mulloch Hill Formation brachiopod fauna indicates an upper half of the Rhuddanian correlating with A_3-A_4 in the type Llandovery area. The biostratigraphical constraint of the Newlands Formation - in that it is underlain by the Glenwells Shale containing an upper *cyphus* graptolite assemblage and overlain by the *gregarius* zone graptolite assemblage of the Glenshalloch Shale, suggests an age of lower Aeronian (Cocks et al., 1984). Though the graptolites within the Newlands Formation, including *Monograptus* sp. and *Dictyonema* are not diagnostic of age, this age is confirmed by the brachiopod fauna, yielding the only middle Llandovery, Aeronian shelly fauna in Scotland.

Some unidentifiable brachiopods were found by Freshney (1959) in the Upper Saugh Hill Grits, but the fossils collected in the overlying Pencleuch Shale by Cocks and Toghill (1973) characterise an upper *convolutus* zone and can be correlated with the Pencleuch Shale of the Main Outcrop, which also yielded a single *M. cf. sedgwicki* and therefore it is postulated to be close to the boundary. Brachiopods including *Eocoelia curtisi* occurring within 5m of the base of the lower Camregan Grits have been dated by Cocks (1971) as top of the *sedgwicki* zone. In addition to the change in faunal composition and lithologies: the apparent juxtaposition of euxinic black graptolitic shales with bioclastic fine- to medium-grained sandstone and the absence of most of the *sedgwicki* zone, Cocks & Toghill (1973) postulate a stratigraphical break at the base of the Lower Camregan Grits.

CHAPTER 2

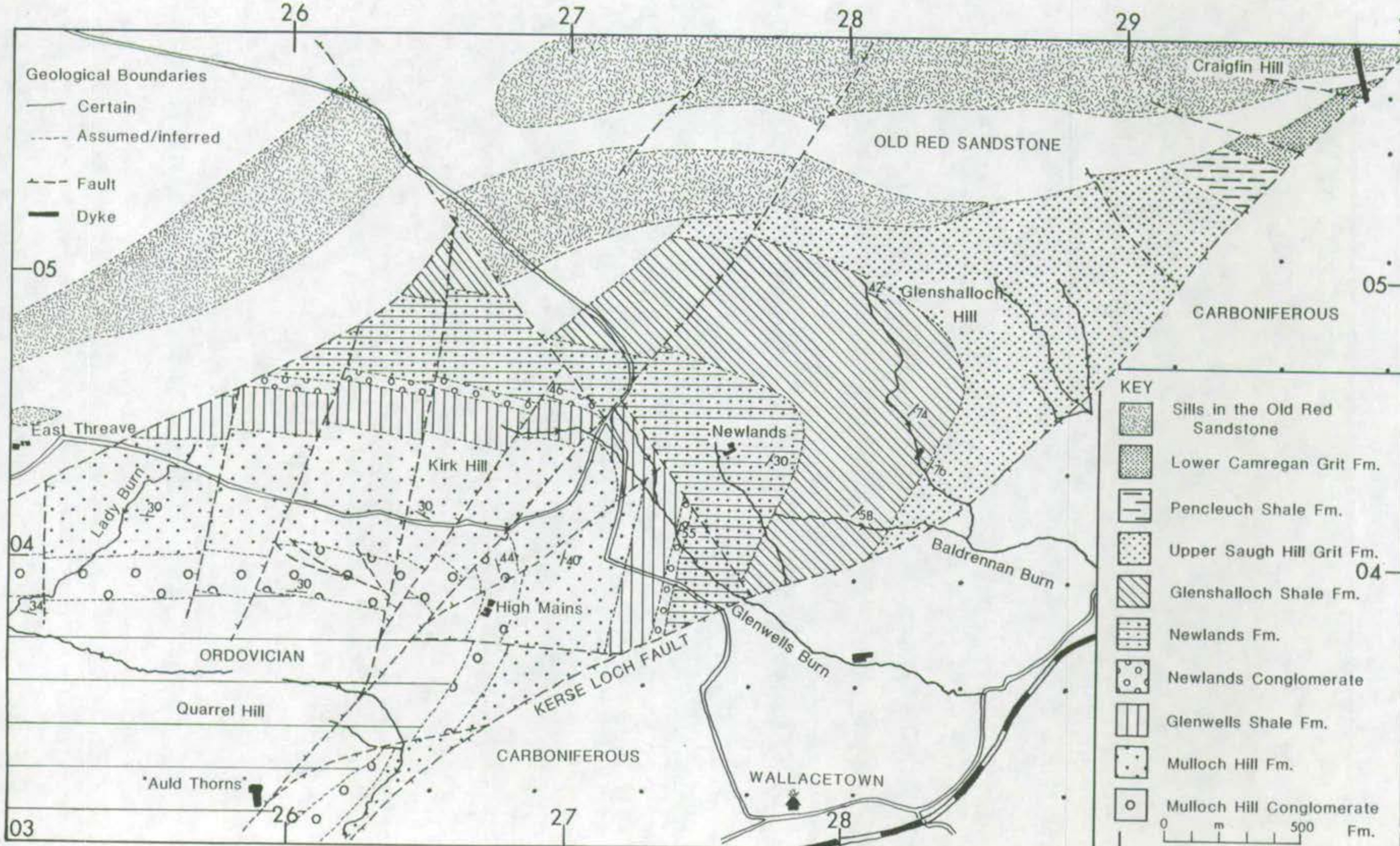
2. GEOLOGY OF THE SILURIAN ROCKS IN THE CRAIGHEAD INLIER

2.1 INTRODUCTION

On the basis of variations in lithological character, the Silurian sediments have been divided into stratigraphical units which comply with the ISSC (International Subcommissions on Stratigraphic Classifications) guidelines (Hedberg, 1976). Where appropriate, formations were divided into members, recognised as such because of some individual lithological peculiarity. By contrast with Cocks and Toghill (1973), it is preferred, here, to retain some of Lapworth's useful major group names, which group naturally related formations together. Redefinition of the formations was necessary in order to resolve confusion arising from differing practices of workers, such as problems with the lithostratigraphy and local correlation. Although the units are lithologically diverse and lithic designators are, in general, rather misleading, the author has retained the original lithic designators in order to remain consistent with previous literature. For ease of reading the full names of the lithological units are given in the titles and figures but are abbreviated within the text by omitting the last word 'Formation', for example Mulloch Hill Conglomerate.

The following account describes each formation present at Craighead, and at the coast (Chapter 3) and is accompanied by an interpretation of the sedimentological evidence. Outcrop numbers in the text refer to those plotted on the geological map (Fig. 2.1*). Owing to the lack of exposure, particularly the lack of exposures displaying contacts between the various formations, and the complications of excavating trenches, the illustrated geological maps exhibit two forms of geological boundaries. The solid line represents an actually exposed boundary whereas a short broken line represents an assumed boundary (which has been either calculated or has been inferred). Colour of the lithologies is defined using the 'Rock Color Chart' (Goddared et al., 1984).

*(Fig. 2.1) Large-scale geological map of the Craighead Inlier Map in the back pocket.



Fig(2.1) Geological map of the Craighead Inlier.

2.1.1 Structure of the Craighead Inlier

The Craighead Inlier is characterised by an asymmetric anticline whose fold axis trends southwest-northeast (Fig. 2.2). Ordovician rocks namely the Drummuck Group occupy the core of the anticline and are surrounded by Silurian rocks which become progressively younger to the northeast. The northern limb dips gently at c.30^{o} whilst the southern limb is markedly steeper and is truncated by a large fault (known as the Kerse Loch Fault) trending southwest-northeast, whilst a series of minor faults trending north to south dissect the northern limb. Minor intrusions are very scarce - only one dolerite dyke is known, intruded into the Glenshalloch Shale in Baldrennan Burn.

In the north the Silurian sediments are unconformably overlain by Lower and Upper Old Red Sandstone and volcanics, whereas in the south the sediments are faulted against the Carboniferous, along the Kerse Loch Fault. Abrupt convergence of the Kerse Loch Fault and the unconformity at the base of the Upper Old Red Sandstone towards the northeast reduces the area occupied by the Palaeozoic rocks, such that in the wooded hills of Craigfin the Silurian rocks disappear.

2.1.2 Ordovician-Silurian Junction

For a long time the Ordovician-Silurian boundary at Girvan has been a point of contention. In recent years it has been believed that the Mulloch Hill Conglomerate, of Silurian age, oversteps and overlaps older Ordovician rocks in a southwesterly direction (Cocks and Toghill, 1973; Harper 1988). This, however, was no more than an assumption since there is a singular lack of exposures where the contact can actually be observed. In order to test this hypothesis, exposures were excavated, during the programme of fieldwork, near the postulated junction.

Near the head of the Lady Burn in Craighead (locality 73, NS 252039) and almost perpendicular to the course of the burn, the Mulloch Hill Conglomerate crosses the little stream and forms a small waterfall (Fig. 2.1). A few metres downstream the underlying Ordovician is represented by the South Threave Formation which appears shattered and splintery. Excavations made near the postulated junction revealed a shattered and friable conglomerate matrix. So although the contact may be a normal unconformity, there is some evidence of faulting at that particular locality, and for the moment, pending further investigation, the question must be left open.

In the vicinity of High Mains farmhouse, however, the terminal Ordovician unit, the High Mains Formation, of Hirnantian age, is overlain by the Mulloch Hill Conglomerate and the junction is assumed to be fairly sharp with a slight angular discordance (Harper, 1988).

2.2 THE GEOLOGY OF THE CRAIGHEAD INLIER

2.2.1 Mulloch Hill Conglomerate Formation

The Mulloch Hill Group defines a natural grouping of Formations, namely the Mulloch Hill Conglomerate, and the Mulloch Hill and Glenwells Shale Formations which demonstrate a single fining-upwards sequence.

In accordance with Lapworth, and Harper (1982), the name Mulloch Hill Conglomerate is retained here in preference to the recently proposed Lady Burn Conglomerate of Cocks and Toghill (1973) since the term 'Lady Burn' has already been widely used following Lamont (1935) to describe a well known unit in the Upper Drummock Group.

The Mulloch Hill Conglomerate represents the base of the Silurian in the Craighead Inlier and its estimated thickness is 90m (Fig. 2.2). It is characterised by a very poorly-sorted polymict conglomerate, composed of pebble-to cobble-grade clasts, as large as 14cm in diameter, which are generally of low sphericity yet fairly well-rounded. Acidic, plutonic igneous rocks are abundant as well as high-grade metamorphics, chert, jasper and quartzite, embedded in a very sandy matrix. Exposures of the conglomerate tend to form low topographic mounds, possessing a scarp and dip slope.

The Mulloch Hill Conglomerate is subdivided into three members; a lower member of conglomerates interbedded with sandstones, a middle member of grey, thinly-bedded sandstones, and an upper conglomerate member.

Above Quarrel Hill the conglomerate forms a ridge over 50m long and over 20m wide, locality 13 (NS 259039), which is displaced by a fault trending in a northeast to southwest direction (Plate 1.1.1). Here the conglomerate horizons are regularly interbedded with very coarse-grained lithic arenites (Fig. 2.3 and 2.4). The conglomerate is very poorly sorted with clasts ranging from pebble-to cobble-grade, from 0.6-14cm. Maximum clast size does not exceed 14cm. Most of the clasts are subrounded to well rounded, varying from tabulate to bladed in shape (Plates 1.1.2 & 3). Superficially the clasts appear to be embedded in a purple-coloured, sandy matrix (Plate 1.1.4). However, under petrographic examination the matrix is in fact found to be composed of the products of the degradation of the component clasts, suggesting that the original conglomerate was grain-supported. There is no evidence for internal organisation such as grading, stratification or preferred orientation of the clasts within the conglomerate. Generally bed thickness varies between 0.20 to 1.80m, with a mean thickness of 0.75m.

Fig(2.3) Key to log symbols.

LITHOLOGICAL SYMBOLS

- Boulder conglomerate
- Cobble conglomerate
- Pebble conglomerate
- Clast supported
- Matrix supported
- Sandstone(fs.ms.cs.)
- Sandstone with pebbles
- Siltstone(s)
- Shale(m)

SEDIMENTARY STRUCTURES

- Normal grading
- Reverse grading
- Parallel lamination
- Low angle cross bedding
- Trough cross bedding
- Asymmetrical ripples
- Flute casts
- Groove casts
- Tool marks
- Load casts
- Dish structures
- Lineations or striations
- Styolites
- Intraclasts
- Imbrication

BED CONTACTS

- Sharp,planar
- Irregular
- Gradational

BIOGENIC STRUCTURES

- Fossil horizon
- Burrow
- Bioturbation
  - moderate
  - intense

PALAEONTOLOGICAL SYMBOLS

- Bivalve
- Brachiopod
- Bryozoan
- Solitary coral
- Compound coral
- Crinoid
- Gastropod
- Cephalopod
- Trilobite
- Ostracod
- Starfish
- Graptolite
- Dendroid
- Algae
- Fossils (undifferentiated)

Fig(2.3) Key to log symbols.

ABBREVIATIONS OF LITHOLOGIES

m	Mudstone
s	Siltstone
F	Fine-grained sst
m	Medium-grained sst
c	Coarse-grained sst
vc	Very Coarse-grained sst
g	Gravel
p	Pebble conglomerate
c	Cobble conglomerate
b	Boulder conglomerate

MISCALLANEOUS

Micro faults

Boudinage

Slumps

Folding

Nodules

KEY FOR CHAPTER 4

ABBREVATIONS

eq	Equant
tab	Tabulate
blad	Bladed

ang	Angular
suba	Subangular
subr	Subrounded
r	Rounded
wr	Well rounded

Clast shape

○ ○	Equant
□ □	Tabulate
⬭ ⬭	Bladed
═	Rod

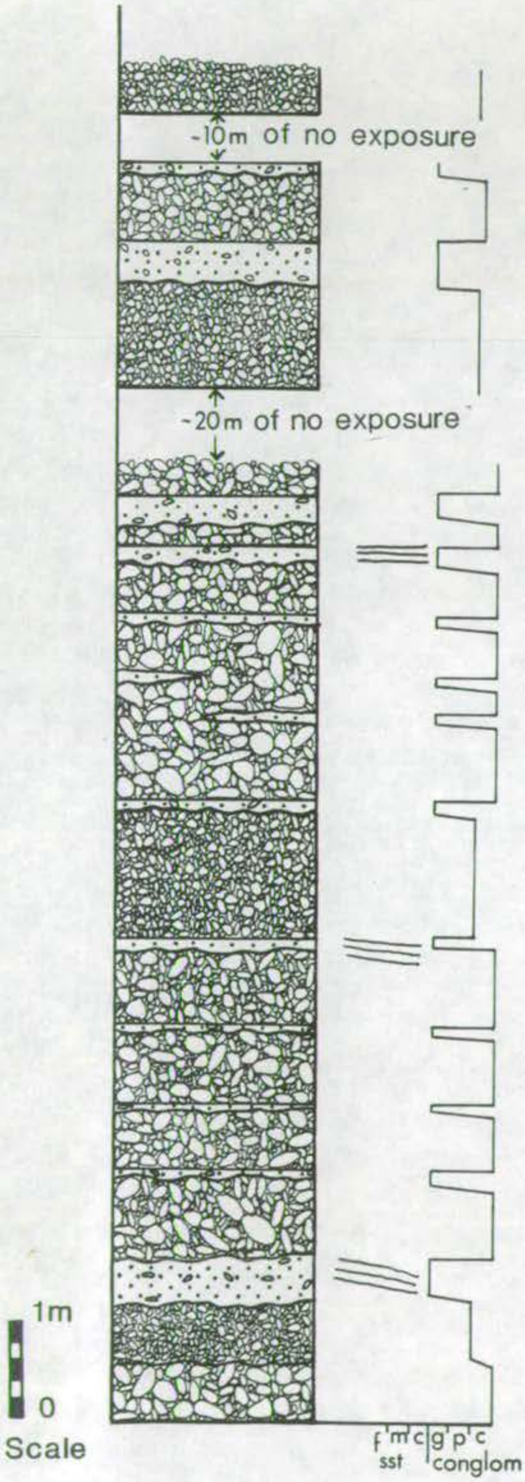
Clast sphericity

○ ○	High
V	Moderate
‾_‾	Low

Clast roundness

• •	well rounded
○ ○	rounded
‾_‾	Subrounded

MULLOCH HILL CONGLOMERATE FORMATION



Locality 6
Polymictic pebble conglomerate with small (max. diameter 5 cm) well rounded pebble clasts.

Locality 7

Clast supported,poorly sorted pebble conglomerate
Max. clast size:6 cm.

Locality 13

Laminations defined by subtle grain size differences.

Polymictic cobble conglomerate.Clast composition includes : basic to acidic igneous rocks, low grade metamorphic rocks, chert and jasper.
The unit contains a number of laterally discontinous sandstone lenses.

Moderately sorted,coarse grained sandstone.
Floating pebbles absent.

Thinly bedded sandstone with a gradational base and sharp top.

Very coarse grained sandstone with small pebbles up to 3 cm floating in the groundmass.

Very poorly sorted,clast supported conglomerate
Max. clast size:17 cm diameter

Fig(2.4) Stratigraphic sections through the Mulloch Hill Conglomerate Formation .

Contacts between the conglomerates and the overlying sandstones are gradational, in that there is a transition of approximately 1-2cm from conglomerate to sandstone (Fig. 1.1.5-7), whilst the tops of the sandstone beds are sharp. Bed thickness ranges from 0.09 to 0.43m with a mean thickness of 0.20m, and the beds are laterally traced for short distances, in terms of tens of meters. These lithic arenites are coarse-grained (0.2-0.5mm diameter) and frequently contain pebbles ranging from 0.5 to 3.0cm diameter, floating within them (Plates 1.2.1 & 2). Usually the pebbles are aligned with the long axis parallel to bedding. In the lower sandstone units of locality 13, low-angle and trough cross-bedding are present (Plates 1.2.3) and occasionally the laminations are truncated by a much coarser granular sandstone (Plate 1.2.4). Towards the top of the locality the cross-bedded sandstones are overlain by parallel-laminated sandstones, commonly 0.20-0.30cm thick (Plate 1.2.5 & 6). The laminations are defined by subtle grain-size differences; the coarser laminations are up to 1.3cm thick, composed of very coarse sand-sized grains up to 0.1cm diameter, whereas the finer laminae are approximately 0.6cm thick with grains less than 0.1cm diameter (Plate 1.2.3).

Stratigraphically higher up in the sequence, at locality 6 and 7 (NS 261039) the conglomerates form elongate mounds. Like the underlying conglomerate, the conglomerates are poorly sorted, and grain supported, with no internal organisation. The clasts are of similar composition to those of the lower beds, although there is a slight decrease in clast size. Maximum-clast size is 9.0cm diameter, and the general range is 0.3-0.9cm diameter (Fig. 2.4).

The middle member is exposed at locality 1 (NS 261041) (Plates 1.3.1 & 2) and is represented by medium-grained (0.3mm) lithic arenites. Originally Lapworth (1882) referred to these very thinly bedded sandstones as 'tilestones' because they weather into very thin sheets, ranging from 0.7-2.5cm in thickness. Occasionally very faint laminations can be seen, whilst primary current lineations are present on the soles of the beds. Dispersed throughout the sandstones are small pebbles ranging in size from 0.4 to 6.0cm diameter, with a maximum clast size of 6.0cm diameter. One thin (4-8cm) conglomerate lens was traced for up to 3m and was composed of poorly-sorted, well-rounded, tabulate to elongate pebbles embedded in a sandy matrix. Within the sandstones a few fragmented brachiopods and crinoid ossicles were present.

The upper member returns to the poorly-sorted, grain-supported polymict conglomerates. Continuing the gradual reduction in maximum clast size, from 14cm at locality 13 to 9cm diameter at locality 4 (NS 259041), the clasts range from 0.1 to 9.0cm in diameter.

Interpretation

The sandstones' boundaries with the cobble conglomerates are fairly sharp yet gradational, indicating a waning current as opposed to two separate flows.

The conglomerates were probably rapidly deposited by very viscous debris flows, composed of clasts carried generally by a watery mud matrix (Reading, 1982). Although they offer resistance to shear strength, above a certain point, the yield value, flow will occur, and they will move relatively slowly down-slope until the downslope gravity vector no longer exceeds the shear strength of the debris. Consequently they come to a sudden halt, thus accounting for the general lack of internal structures.

A transition from debris flow to high density turbidity currents is reflected by the gradational boundary between the conglomerate and sandstone. The sandstones are the products of rapidly declerating high density turbidity currents and were rapidly dumped, accounting for their lack of sorting and the pebbles floating within the sandstone. The coarse to fine laminations within the sandstone are caused by the pulsating deceleration of the turbidity current, whereas the trough and low-angle tabular cross-beds were produced by migrating sinuous, crested mega-ripples and are independent of water depth. Present day debris flow deposits are best known on gentle slopes of less than one or two degrees, but it is here postulated that the Mulloch Hill Conglomerates were deposited in shallow water because of the presence of fragmented brachioods and crinoid ossicles higher up in the thinly bedded sandstones, indicating a very shallow shelf, submarine, near-shore environment.

Submarine fans and associated deep-sea channels are a major type of sedimentary deposit ascribed to turbidity-current processes. In a simple system, a fan-shaped wedge of sediment will be deposited and radiate outward from the lower end of a canyon. Generally it is recognised that most submarine fans can be divided into three physiographic zones which display distinctive morphologies, sedimentary processes and depositional patterns. These are 1) the inner (or upper fan), 2) the middle fan with suprafan lobes and 3) the outer (lower fan). These are briefly described here with a fuller discussion of the characteristics of the physiographic zones.

1) The inner fan has steep gradients and sediment transport is concentrated down a main fan valley which may be straight or sinuous.

2) In the middle fan, the main valley splits up into many distributaries (fan channels). The channels may meander or branch down-current into numerous distributaries which, as the channels shift and are abandoned, give rise to fining-upward sequences.

3) The outer fan is essentially devoid of erosively based channels and passes gradually into the outer fringe and basin plain.

Mutti (1974, 1977), Walker and Mutti (1973), and Ricci-Lucchi (1975) have related sequence types to the morphology of submarine fans. Thickening-upward sequences are interpreted as due to the advance of prograding lobes at the front of the suprafan, with variations in the sequence being the result of switching supply. Thinning-upward sequences are characteristically channelled, and are the results of the progressive abandonment of the channel, as a new one is developed.

Although fans, in general, have several fundamental features in common which can be combined to construct a unified fan model, fans may differ in many respects, for example size, nature and number of sediment sources.

The coarse, disorganised conglomerates in the Mulloch Hill Conglomerate which unconformably overstep and overlie two Ordovician fans in the Craighead Inlier were probably deposited in the inner fan channel.

Judging by the coarsest clast size of 14cm diameter, supply and transportation of the coarse material was fairly localised, although Embley (1976) and Moore et al. (1976) have reported recent debris flows travelling several hundreds of kilometers and covering areas of many thousands of square kilometers. These deposits could represent the influx of coarse material along a newly inaugurated fault margin. Possibly the material was dumped at the top of the slope and subsequent overloading would initiate debris flows. The conglomerate-sandstone couplets record the deceleration of the debris flows, and the transition into turbidity currents.

The thinly-bedded sandstones possessing primary current lineations, in the middle member, were deposited in the upper flow regim associated with high velocity currents. These thinly-bedded, graded beds compare closely with, and may be mistaken for, distal turbidites, yet they occur in distinct proximal associations and are probably the products of turbidity currents flowing of debris flows.

2.2.2 Mulloch Hill Formation

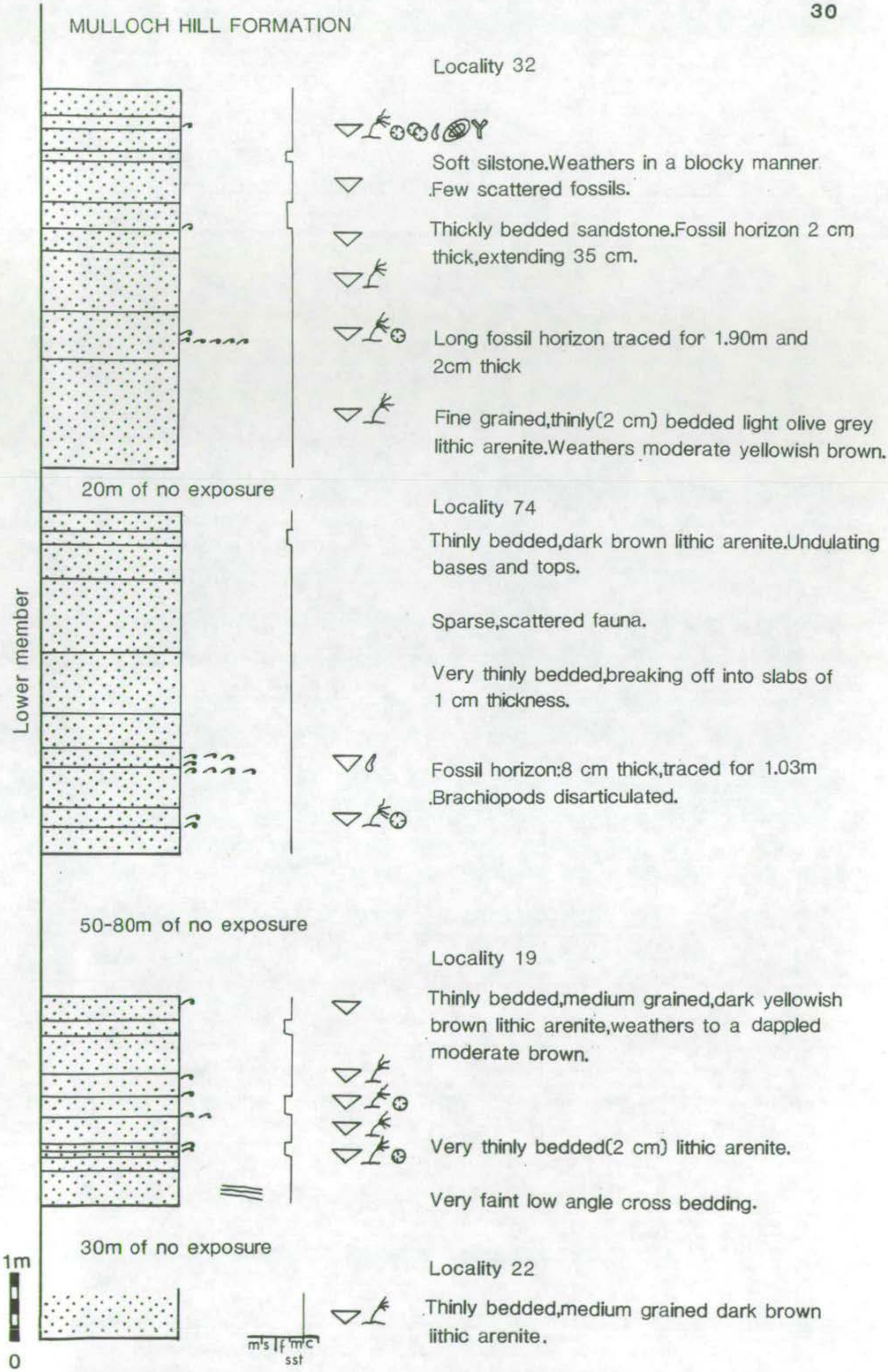
This sequence has been traditionally referred to as the Mulloch Hill Sandstone. It consists of lithologies other than sandstones, however, including purplish and green coloured fine-grained siltstones and shales, and the original name is inappropriate. The term Mulloch Hill Formation is here preferred, following Cocks and Toghill (1973), which in any case is in agreement with standard stratigraphic practice. Exposures of the Mulloch Hill Formation may be found on the summit and flanks of Kirkhill, particularly in a number of small quarries along the rough hill-road, lying to the north of High Mains Farm, and in the small burns descending through the High Mains Wood. In the southeast there are a few exposures below the ruins of Auldthorns, in the low-lying flat area of Quarrel Burn. There the exposures are displaced by a number of faults and are inverted, pinching out near Kildrummie, where the major faults of Quarrel Hill and Craighead converge.

The boundary between the underlying Mulloch Hill Conglomerate and the Mulloch Hill Formation is not exposed. It is envisaged as being conformable and gradational because of the progressive reduction in clast size from the underlying conglomerate to sandstone and the similarity in composition. The Mulloch Hill Formation is up to 220m thick. On the basis of colour, both Lamont (1935) and Freshney divided the Mulloch Hill Formation into two parts, namely; the lower, 'Rough Neuk', or 'Green' Sandstones and the overlying 'Craigens', or 'Buff' Sandstones respectively. Later Cocks and Toghill (1973) stated that the Rough Neuk Quarry in fact overlies Lamont's Craigen's quarry and as the ochreous weathering does not appear to be concentrated in specific horizons they believed the subdivisions to be unfounded.

The present author accepts that the original subdivision based upon colour differences alone can be disregarded and instead proposes a new subdivision into three members. These are 1) lower, flaggy sandstones, 2) the sandstones and siltstones of the Mulloch Hill Road and 3) the Upper Rough Neuk Sandstone within which occurs the Rough Neuk Starfish bed (Fig. 2.5 & 2.6).

The lower member consists of alternating medium-to thickly-bedded fine-grained lithic arenites. At locality 19 (NS 258041) the sandstones have a dark yellowish-brown colour weathering to a rather dappled moderate brown. Average bed thickness is 0.26m, whilst the range is from 0.15-0.50m (Fig. 2.5 & Plate 1.3.3). There is a tendency for the beds to have undulating bases and tops, defined by a few centimeters of uneven relief (Plate 1.3.4). Superficially these resemble hummocks as seen at locality 74 (NS 255042) (Plates 1.3.5 & 6), but this may only be the effect of a combination of compaction and weathering (pers. comm. C. Mehretens and J.M.L. Cater). Fossil horizons are concentrated either near the base or towards the top of the beds, in horizons up to 4cm thick and traceable for up to 50cm (Plate 1.3.7). Faunal diversity is low; the dominant fossils are brachiopods, there are also a few gastropods and loose crinoid ossicles.

Slightly higher up in the sequence, at locality 32 (NS 265042), fine-grained light olive-grey weathered moderate yellowish-brown coloured sandstones alternate with siltstones (Plate 1.3.8). Maximum grain size is approximately 0.15mm. The lithologies are thickly bedded with bed thickness ranging from 0.39m to 1.08m, and an average of 0.77m. Apart from laminations, sedimentary structures are lacking (Fig. 2.5). As with locality 19 and 74 the fossils occur either near the base or the top



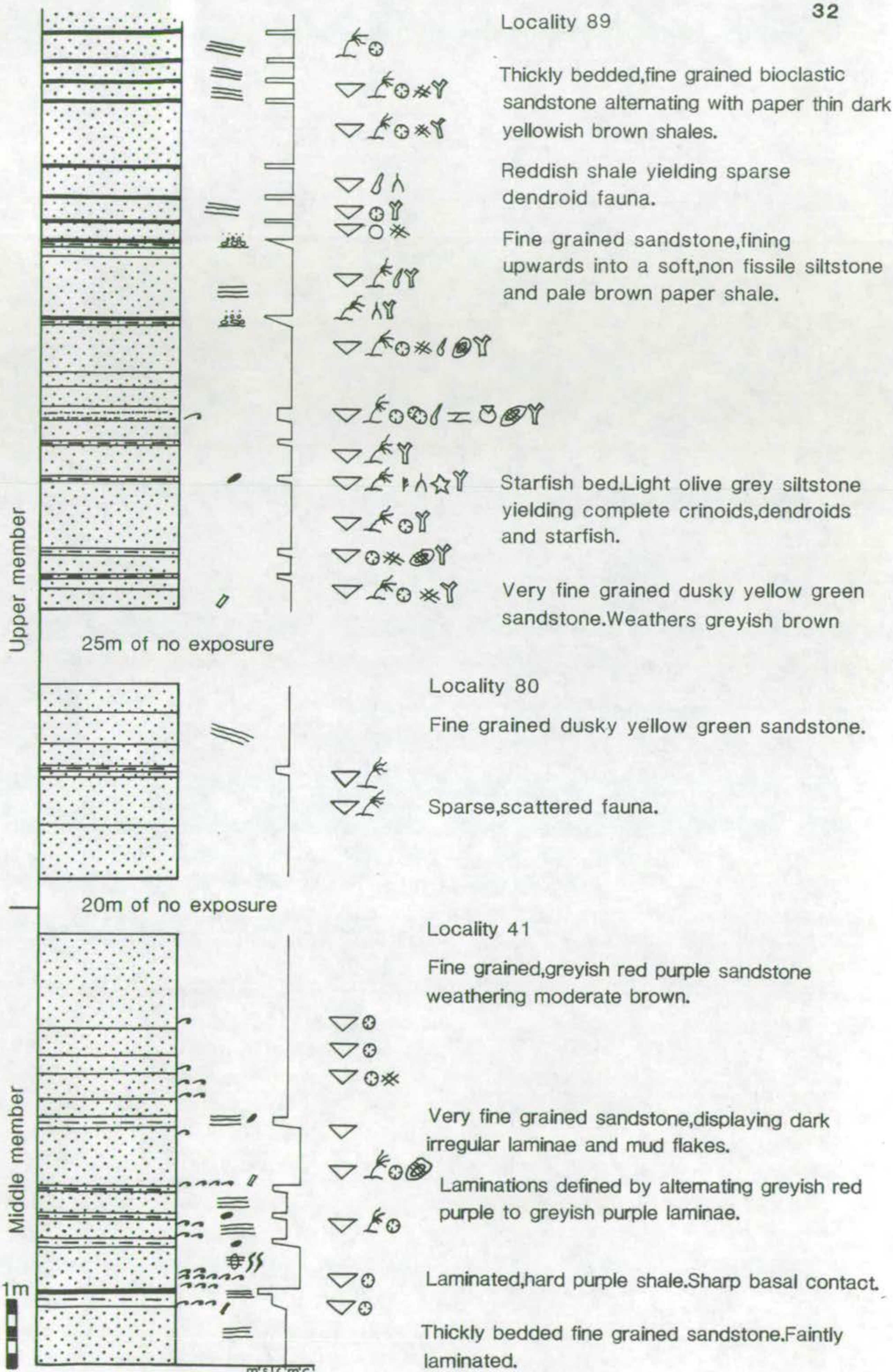
Fig(2.5) Stratigraphic section of the Mulloch Hill Formation.

of a sandstone unit, and generally comprise of a low diversity fauna of brachiopods, crinoid ossicles, gastropods and rare solitary corals.

Contrasting significantly with the underlying monotonous sandstones, the middle member exposed in a small quarry beside the Mulloch Hill High Road at locality 41 (NS 265042), (Plate 1.4.1) is characterised by thickly-bedded fine-grained greyish-red to purple coloured sandstones (weathering to a moderate-brown intercalated with thinly-bedded siltstones (Fig. 2.6)). The maximum grain size for the fine-grained sandstones is approximately 0.3mm. Bed thickness varies from 0.28 to 1.40m with an average of 0.88m. Laminations in the siltstones are discriminated by subtle alternations in colour from greyish-red to purple to greyish-purple and are approximately 0.3 to 0.2cm thick, respectively. On some bedding surfaces small black mud flakes with a maximum diameter of 1.6cm are present. As well as some anomalously larger pebbles, (for example one granite clast was as large as 0.9cm in diameter) there are a few elongate mud clasts present whose long axis does not exceed 0.7cm. Nine fossil horizons are present, confined usually to the base of the fine-grained sandstones (Plate 1.4.2). Normally they are less than 6cm thick and can be recorded for up to 1.5cm. There is no change in the diversity of the fauna.

What distinguishes this lithofacies from the underlying sandstones, is the presence of a low-diversity ichnofauna. In the lower beds of locality 41, many of the thickly bedded sandstone units are internally bioturbated and consequently many flasers and laminations appear disrupted. Furthermore, two vertical straight burrow structures were found measuring 0.5cm by 0.25cm and they were seen to truncate and even arch up the laminae.

Deriving its name from the very large open quarry in the High Mains Wood (locality 89, NS 271039), the upper member of the Mulloch Hill Formation is referred to as the Rough Neuk Sandstone Member. Fortunately the very top third of the Wood was recently felled, continuing a reafforestation programme which during the course of field work allowed easy access to the quarry (Plate 1.4.3). At Rough Neuk the lithofacies are represented by fine-grained parallel-laminated and cross-laminated sandstones and siltstones frequently fining up into paper shales (Fig. 2.6 & Plate 1.4.4). The sandstones are very fine-grained with an average grain size of 0.1mm, although occasionally there are small granules up to 0.2cm in diameter. When weathered they possess a greyish-brown colour but internally they have a dusky yellow-green colour. Bed thickness varies from 0.15 to 1.00m, with an average of 0.29m. Throughout the sandstones, very thin, less than 1mm thick, black stylolites are present. Very faint parallel laminations and cross laminations are defined by changes in colour from dusky yellow-green to a greyish-purple. The



Fig(2.6) Stratigraphic section of the Mulloch Hill Formation.

latter are thinner not exceeding 0.05mm whilst the green laminae vary in thickness from 0.15 to 0.6cm.

The siltstones vary in thickness from 2 to 10cm. The boundaries between these siltstones and the very fine-grained sandstones are very gradational. Unusually, they weather into blocks whose upper surfaces are slightly convex, and are occasionally topped by a very thin, pale-brown coloured paper shale which weathers to a greyish-red. Sedimentary structures such as sole markings have not been found.

Near the middle of the Rough Neuk Sandstone Member, the Rough Neuk Starfish Bed occurs (horizon 13, Plate 1.4.6). It is a thinly bedded (less than 5cm thick) light olive-grey coloured siltstone in which small black irregular-shaped mud flakes less than 1.0cm diameter are present. The principal constituents of its fauna are abundant dendroid fragments as well as starfish and completely articulated crinoid specimens (Plate 1.4.7).

This fauna contrasts markedly with the rest of the Rough Neuk Fauna, which is dominated by articulate brachiopods supplemented by bryozoans, algae, trilobites, bivalves and cephalopods. The fossils occur as either thin (2-3cm thick) fossil concentrations traceable for up to 0.80m or are scattered throughout the sediments. The effects of bioturbation and burrowing are lacking in the Rough Neuk Sandstones Member contrasting with the middle member at locality 41. Towards the top of the Mulloch Hill Formation, as seen in Rough Neuk, faintly laminated siltstones are interbedded with thin, dark yellowish-brown coloured paper shales, yielding a sparse dendroid fauna. (Plate 1.4.5).

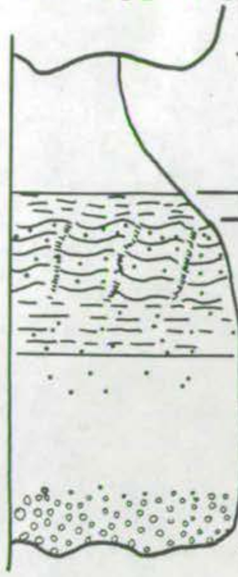
Interpretation

Turbidite Model

As previously mentioned the sediments of the Craighead Inlier have been interpreted by Cocks and Toghill (1973) as the products of turbidity currents.

Turbidity currents are slurries of sediment and water, which flow down a slope at remarkably high speeds, covering vast distances. The sediments deposited are termed turbidites. Each turbidite is the result of a single, short lived event. In the field, turbidites are identified by a set of distinctive structural characteristics including; alternating coarse and fine-grained beds, laterally continuous and regular beds, the presence of vertical grading and sole structures, such as scours (flutes) and tool (groove) marks. Detailed examination of turbidites resulted in the recognition of a generalised model, namely the classic Bouma sequence (Bouma, 1962) consisting of five divisions (Ta-Te) recording sediment structures produced by decreasing flow rate (Fig. 2.7). Initially, a current scoured a variety of structures on a mud surface, accounting for the scour marks. Then sedimentation took place under waning

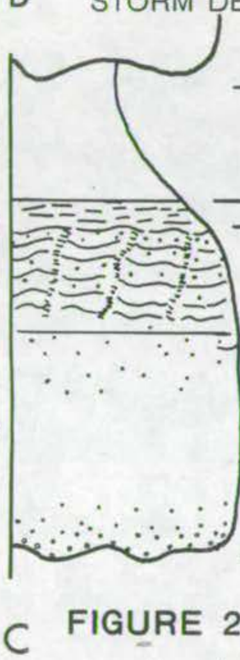
A BOUMA SEQUENCE



		Divisions	Interpretation
T_e	mud	Interturbidite (generally shale)	Pelagic sedimentation of fine grained, low density turbidity current deposition
T_d	silt	Upper parallel laminae	? ?
T_c	sand	Ripples, wavy or convoluted laminae	Lower part of the Lower Flow Regime
T_b		Plane parallel laminae	Upper Flow Regime, plane bed
T_a	sand	Massive, graded	Upper Flow Regime, rapid deposition

B STORM DEPOSITED BED

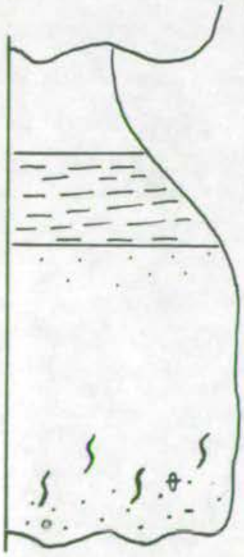
FIGURE 2.8



		Division	Interpretation
S_e	mud	Upper mud cap	Settling of the finer particles
S_d	silt	Parallel laminated, fine sand to silt	
S_c		Cross and convoluted laminae	Lower part of the Lower Flow Regime
S_b	sand	Medium to fine grained sand	Upper Flow Regime, rapid deposition

FIGURE 2.9

C Locality 41



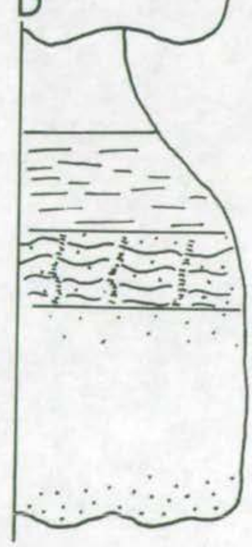
Upper mud cap

Parallel laminated, fine grained sand

Medium to fine grained sand

FIGURE 2.10

D Locality 89



Upper mud cap

Parallel laminated, fine grained sand

Low angle cross laminae

Medium to fine grained sand

MULLOCH HILL FORMATION

current conditions, depositing a massive unit Ta, under an upper flow regime, after which shooting flow deposited the laminated Tb unit. A a lower flow regime deposited the micro-cross-laminated Ta unit, and upper laminated silt, unit Td. Finally unit Te, the upper pelitic unit, indicates a resumption of the low-energy environment which prevailed before the turbidite was laid down (Fig. 2.7). Mutti and Ricci Lucchi (1972) and Walker (1967, 1970, 1978) have further subdivided turbidites into a number of facies ranging from A-E, based on grain size, bed thickness, sole marks, and internal structures. Facies A is represented by coarse-grained sandstones and conglomerates, Facies B by medium-to fine-to coarse-grained sandstones, Facies C-E are comparable to the Bouma sequence, and Facies F & G are not applicable to the Bouma sequence. Facies F represents the chaotic deposits formed by downslope mass movements, whilst the pelagic and hemipelagic shales of facies G were deposited by very dilute suspensions.

Using this as a basis for interpretation, the lower thickly bedded sandstones of localities 19, 74 and 32 are not comparable to the classic Bouma sequence and as they exhibit sub-parallel lamination but lack concave upward laminae (dish structures), they could be interpreted as a B_2 facies (Mutti and Ricci Lucchi, 1972 and Walker, 1967, 1970, 1978). Whereas locality 41, representing the middle member can loosely be regarded as Facies C, with units described in terms of Ta-Tb-Te of the Bouma sequence, where units possess sharp flat bases and regular bedding. The turbid mud layers at locality 41 may have been deposited by low density, low velocity flows (Moore, 1969) producing homogeneous, delicately laminated (Rupke and Stanley, 1974) and graded muds. These differ from the pelagic structureless shales from Rough Neuk which are poorly-sorted containing sand-sized particles and yield dendroids. The vertical grading displayed in the Rough Neuk Sandstones compare loosely to a Tb-Td-Te (sandstone, siltstone to shale) Bouma sequence. The juxtaposition of bioclastic sandstones composed of skeletal parts of shallow water fauna and shales containing dendroid graptolites may be interpreted as the products of turbidity currents, associated with Facies D. According to Bouma's model the sandstones separated by fine films of shale, near the top of the quarry, comply with a Tb-Te sequence, Facies E.

Therefore it is concluded that the sediments of the Mulloch Hill Formation were deposited by high density turbidity currents. Nevertheless there are a number of discrepancies between the sediments of the Mulloch Hill Formation and typical turbidite sediments in that there is a general lack of well-developed cross-laminated Unit C of the Bouma sequence, and a lack of current-produced primary structures such as flutes and grooves.

Storm Bed Model

An alternative hypothesis advocates storm reworking as the primary or secondary depositional agent.

Recently workers have become more aware of the effects of storms on the nature and distribution of ancient sediments. At first research was concentrated particularly in the Holocene sediments (for example Ball, 1967; Hayes, 1967) but now storm deposited beds are evident in both modern and ancient deposits of epicontinental shelves (Brenner and Davies, 1973; Reineck and Singh, 1975; Kelling and Mullin, 1975; Anderton, 1976). Storm deposit sandstones display several features comparable to turbidites because they similarily form from currents of decreasing strength as indicated by grading with alternating coarse and finer-grained beds and by having sharp erosive bases yet non-erosive tops, parallel laminations, an episodic nature and unit direction (Fig. 2.8). Hunter and Cliffton (1982) conclude that once a shallow marine environment has been determined, a bed may be identified as of probable storm origin on the basis of three kinds of evidence: 1) evidence intially of strong flow followed by decreasing flow rate, 2) evidence of rapid deposition, followed by deposition at a decelerating rate and 3) evidence of oscillatory flow.

It is here postulated that the Mulloch Hill Sandstones were deposited in fairly shallow water. At locality 41, the thickly bedded sandstones, possessing sharp, occasionally erosive tops, the dominance of parallel lamination, the presence of fossil accumulations and bioturbation (Fig. 2.9), indicate that the sediments may have been the products of storms in shallow marine waters, where large volumes of suspended sediments were transported offshore in suspension by decelerating currents. Each bed could be interpreted as recording a single storm event, with several phases. The first phase was initial storm erosion, due to the oscillatory wave reworking or storm current erosion, the second phase deposition when the storm decreased in intensity with parallel laminae forming as sand fell out of suspension, and the third was a post-storm period of reworking and bioturbation. The succeeding storm deposits could have eroded the surface, accounting for the penecontemporaneous erosion of the soft mud substratum, resulting in the inclusion of the intraformational mud clasts. The sediments deposited at locality 41 may have been deposited between the fairweather wave base and the storm wave base and consequently were subject to a fairly high level of agitation. The sediments in Rough Neuk are slightly finer grained, and appear to lack burrows and bioturbation (Fig. 2.10). They were evidently deposited in deeper water below the wave base where there was a marked decrease in the capacity for and duration of periods of erosion. The characteristics of the Mulloch Hill Formation, however, do not accord well with the storm-deposit hypothesis, primarily because of the lack of hummocky cross-stratification normally considered diagnostic of storm deposits. Hamblin and Walker (1979) and Bourgeois (1980) have noted the occurrence of hummocky cross-stratification in nearshore sequences. Hummocky cross-stratification is a distinctive type of low angle cross-stratification (Harms, 1975) which is coming to be recognised as a common feature in many ancient storm deposits (de Raaf et al. 1977; Hamblin and Walker, 1979; Dott and Bourgeois, 1979; Bourgeois, 1980). An older but less widely used name for the same bedding style is truncated wave ripple lamination (Campbell, 1966, 1971; Cotter, 1975). Harms and most other investigators of hummocky cross-stratification have attributed the bedding style to deposition during storms. Unfortunately the structure has not been definitely documented on modern sea floors and therefore their exact mode of formation is unclear. In addition wave ripples, cross laminations, upward-bundling ripples and shelter fabrics are normally abundant in storm deposits, yet they are lacking in the Mulloch Hill Formation.

Reading (1987) points out that the capacity of turbidity currents to deposit sediment with very different characteristics can be underestimated, leading to the mistaken assumption that sediments having few or none of the features diagnostic of typical turbidites were not deposited by turbidity currents. Amongst the features normally considered uncharacteristic of turbidity current deposition in the Mulloch Hill Formation are the following. 1) The palaeontological and sedimentological evidence, in the lower and middle members of the Mulloch Hill Formation, suggests deposition in relatively shallow water. 2) The sediments do not compare well with the typical Bouma sequence, in particular there is a general lack of well developed cross-laminated C units of the Bouma sequence, and a lack of current-produced primary structures such as flutes and grooves on the soles of the beds. However cross-laminae in turbidites can be absent if the necesssary grain size is lacking or if velocities are so high that ripples are planed out (Walker, 1965 and 1967). Furthermore sole marks can be very rare in turbidites when the required specific cohesive mud substrate is lacking. 3) The mud clasts which suggest current reworking of the substratum could also have been ripped up and transported by turbidity currents. 4) The fossils appear to be concentrated in fossil lags, where often disarticulated shells are infilled with mud indicating that, after death and disarticulation, they drifted along the sea floor and were subsequently buried, as opposed to being transported over a great distance. Possibly these fossil horizons formed a traction carpet, produced by high density currents. 5) Finally, the Mulloch Hill Formation does not appear to be stratigraphically sandwiched between fore-shore/shoreface and open shelf sediment, and the underlying Mulloch Hill Conglomerate was deposited by debris flows and high-density turbidity currents.

The Rough Neuk Starfish Bed, yielding dendroids and starfish juxtaposed with the bioclastic sediments, represent an obrution deposit resulting from rapid burial, engulfing and smothering the fauna. The absence of dendroids in the red shales, higher up in the Rough Neuk Quarry, indicates a deficient graptolitic supply or more rapid sedimentation. Therefore it is suggested that intermittent oxidising conditions at the sea-water interface destroyed the dendroids when they reached the sea-floor, and this was then followed by the deposition of the red shale partings (Rust, 1965).

2.2.3 Glenwells Shale Formation

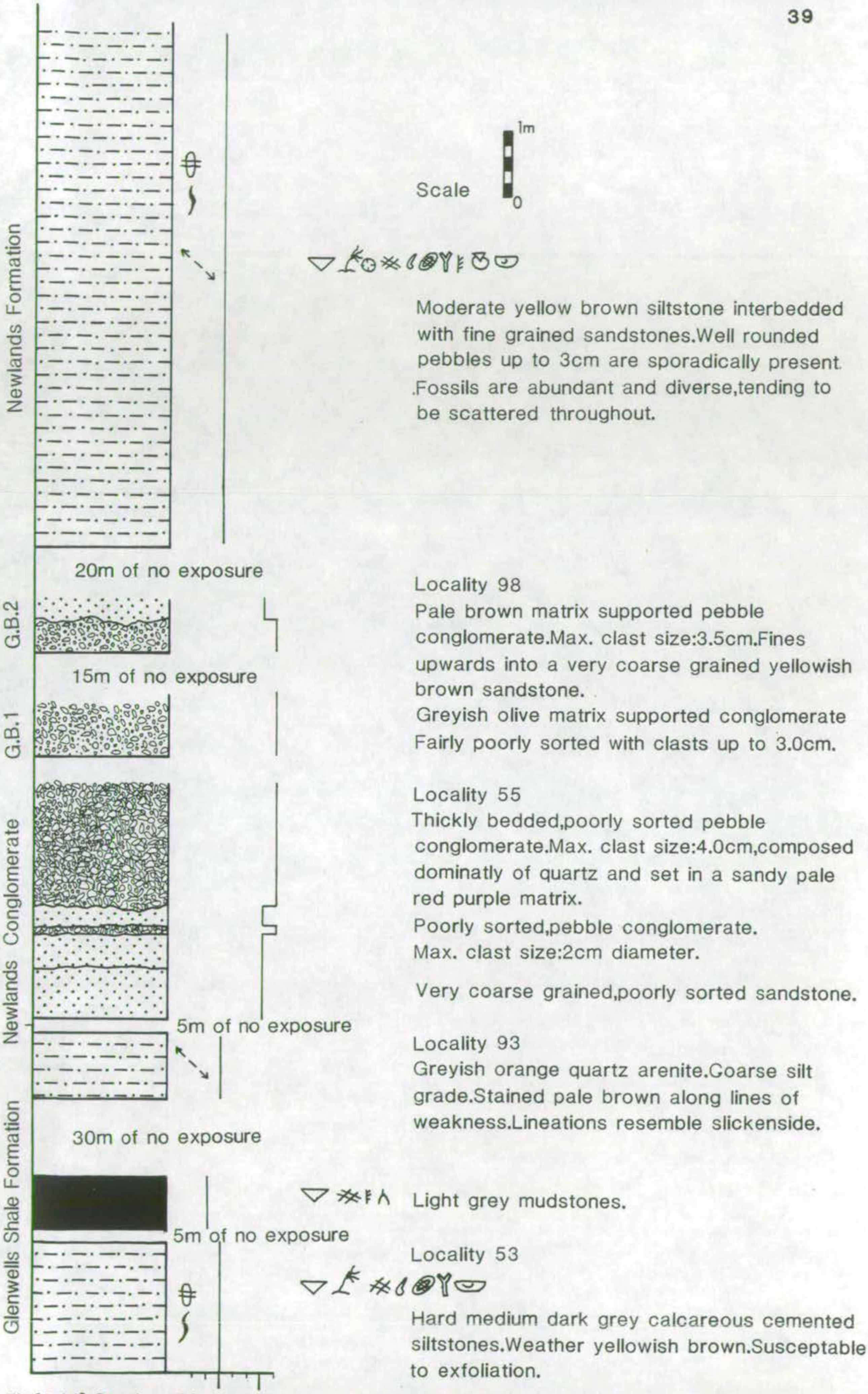
Behind Kirkhill, a fine-grained medium dark-grey coloured calcareous siltstone is exposed in a very small gully, locality 53 (NS 271045), designating the base of the Glenwells Shale (Plate 1.5.1). Formation thickness is estimated at 80m. Due to the poor exposure, the contact between the Glenwells Shale and underlying Mulloch Hill Formation is not seen, but the contact is envisaged as being gradational because of the decrease in sandstone bed thickness, seen at the top of Rough Neuk Quarry, and increase in the shale-sandstone ratio. The Formation is divided into a lower calcareous siltstone, an unfossiliferous mudstone member and an upper, pale-blue graptolite-bearing shale (Fig. 2.11).

The medium-grained (0.01mm) siltstones weather to a dark yellowish-orange colour, and are very susceptible to exfoliation as seen at locality 53 and 54 (Plates 1.5.2-5). Ostracods, brachiopods, trilobites, bryozoans? and gastropods are abundant. Gradually, the siltstone fines up into unfossiliferous light-grey mudstones (Plate 1.5.6). Graptolites and dendroids from the upper member were recovered by Cocks and Toghill (1973) (NS 273041) in the Glenwells Burn - a small burn which flows from the northeast slope of Kirkhill, past Rough Neuk Quarry, to the cottage of Glenwells.

At locality 93 (NS 269046) a medium-grained (0.02mm) quartz siltstone appears to have suffered a considerable degree of tectonic deformation (Plate 1.6.1 & 2). Consequently it has developed a cleavage and joint pattern in two separate directions with additional striae resembling slickensides, suggesting that these rocks occur within the vicinity of a fault plane. Along lines of weakness haematite has been precipitated, staining the greyish-orange coloured quartz arenite a pale brown colour (Plate 1.6.3).

Interpretation

The bioclastic siltstones at the base of the Glenwells Shale were deposited by weak turbidity currents, and may represent Facies G (Mutti and Ricci Lucchi, 1972;



Fig(2.11) Stratigraphic Section of the Glenwells Shale Formation-Newlands Formation.

Walker, 1967; 1970; 1978) whilst the overlying shales trace a gradual transgression into deeper water where the finer fraction settled out. Exemplifying a thinning-and fining-upwards sequence, the Mulloch Hill Group passes upwards into conglomerate (Facies A), sandstone (Facies B, C, D, E) and shale (Facies G). As with modern turbidite fans, ancient fans particularly those of the west coast of North America, have been interpreted in terms of upper, middle and lower fan facies (Mutti and Ricci Lucchi, 1972; Walker and Mutti, 1973). The sequence displayed in the Mulloch Hill Group would appear to correspond with those seen in the Middle Fan, with the coarse material found in the channels (Facies A, B and C) and finer sediments accumulating in the interchannel aeras (Facies D and E). The thinning-up sequence in the Mulloch Hill Group may reflect progressive abandonment, with deposition of thinner and finer beds from smaller and smaller flows in the channel.

2.2.4 Newlands Formation

Recognising that conglomerates occur at the base of the Newlands Formation, Cocks and Toghill (1973) erected a new unit referred to as the Glenwells Conglomerate. The author feels that the name and stratigraphic status is misleading and consequently inappropriate. Therefore it is proposed here that it should be renamed the Newlands Conglomerate Member of the Newlands Formation.

The Newlands Conglomerate Member is exposed at locality 55 (NS 269045), where it forms a crescent shaped exposure on a topographic rise (Plate 1.6.2). Limited exposures hinder calculations of the thickness of this conglomerate unit, but an estimation of between 30-40m is given. The pebble conglomerate is poorly sorted with clasts ranging from 0.5 to 4.0cm diameter, generally not exceeding 7.0cm in diameter (Fig. 2.11) (Plate 1.6.4). Clasts tend to be tabulate to elongate in shape, and subrounded to angular in roundness (Plate 1.6.5). Quartz is dominant and other constituents include chert and igneous clasts which are embedded in a pale red-purple coloured sandy matrix. Generally there is a matrix-supported texture. As no clasts show a preferred orientation and the conglomerate is very thickly bedded (bedding is generally obscured because of the flaggy manner of weathering) there is little evidence for internal organisation. Rarely the conglomerates are interbedded with very coarse-grained (0.5mm) lithic arenites (Plates 1.6.6 & 7). Small elongate to tabulate pebbles, with a maximum diameter of 1cm, float with no preferred orientation in the poorly-sorted sandstones. Bed thickness varies from 0.27 to 0.46m. No fossils were recovered.

By contrast with the aforementioned conglomerate, in Glenwells Burn, locality 98 (NS 274042), the shales are overlain by a greyish-olive coloured, matrix-supported polymict conglomerate (Fig. 2.11). Clasts, ranging in size from 0.2 to 3.0cm diameter,are composed of elongate to subrounded igneous pebbles, noticeably with less quartz, embedded in a green-coloured sandy matrix. The boundary between the conglomerate and overlying green-coloured sandstone is sharp. The sandstone is very coarse-grained, with grains up to 0.1cm in diameter and, although poorly sorted, there are rarely much larger pebbles floating in the sandstones. Bed thickness is estimated at 0.30-0.50cm.

The succeeding conglomerate is distinguished by its pale-brown colour. Within the matrix-supported conglomerate, clasts range in size from 0.1cm to 1.0cm diameter, and are usually less than 3.0cm diameter. Composition of clasts include cherts, quartz and highly altered igneous rocks, and these pebbles tend to have elongate to tabulate shapes and are fairly well rounded.

At locality 99 (NS 275041) the pale-brown coloured conglomerate fines upwards into very fine-grained (0.1-0.04mm), moderate yellowish-brown coloured sandstones and siltstones. These small sections of the Newlands Formation, seen in the dense Glenwells Burn forest are truncated by the Kerse Loch Fault, and only a few isolated exposures are found in the vicinity of the farmstead of Newlands, specifically in a little stream draining the hillslope west of the farmhouse and in an old quarry, a few hundred metres northeast of the farm (locality 124). Scarcity and poor quality of exposures in the Newlands Formation prevented the detailed study of the sedimentological structures (Plate 1.7.1). Apart from the hazy, mottled textures attributed to bioturbation and burrowing, no significant structures were evident. Oval pockets, up to 0.1cm diameter, represent burrow structures which are infilled with finer-grained particles. The fauna recovered from locality 124, a large horse-shoe slip exposure occurring above a little stream (Plate 1.7.2) consists of brachiopods, trilobites, gastropods, corals, algae, bivalves, bryozoans, graptolites and ostracods, qualifying the Newlands Formation as being the only shelly middle Llandovery unit in Scotland (Fig. 2.11). Formation thickness is estimated at 200m.

Interpretation

The Newlands Formation is interpreted as representing the continuation of submarine fan sedimentation. This interpretation is based on: 1) the matrix supported conglomerate beds and 2) the associated siltstones. The deposits of the underlying Glenwells Shale choked up the original channel, thus causing the flow to be diverted into new directions. The geometry of the confined conglomeratic lensoidal exposure at locality 55 and the relative thinness of the Newlands Conglomerate suggests that the sediments represent the products of a single erosional channel building out from the original system into deeper water. Such an autocyclic process can probably be best explained by the rejuvenation of the source area, possibly associated with uplift of the hinterland and tectonic subsidence.

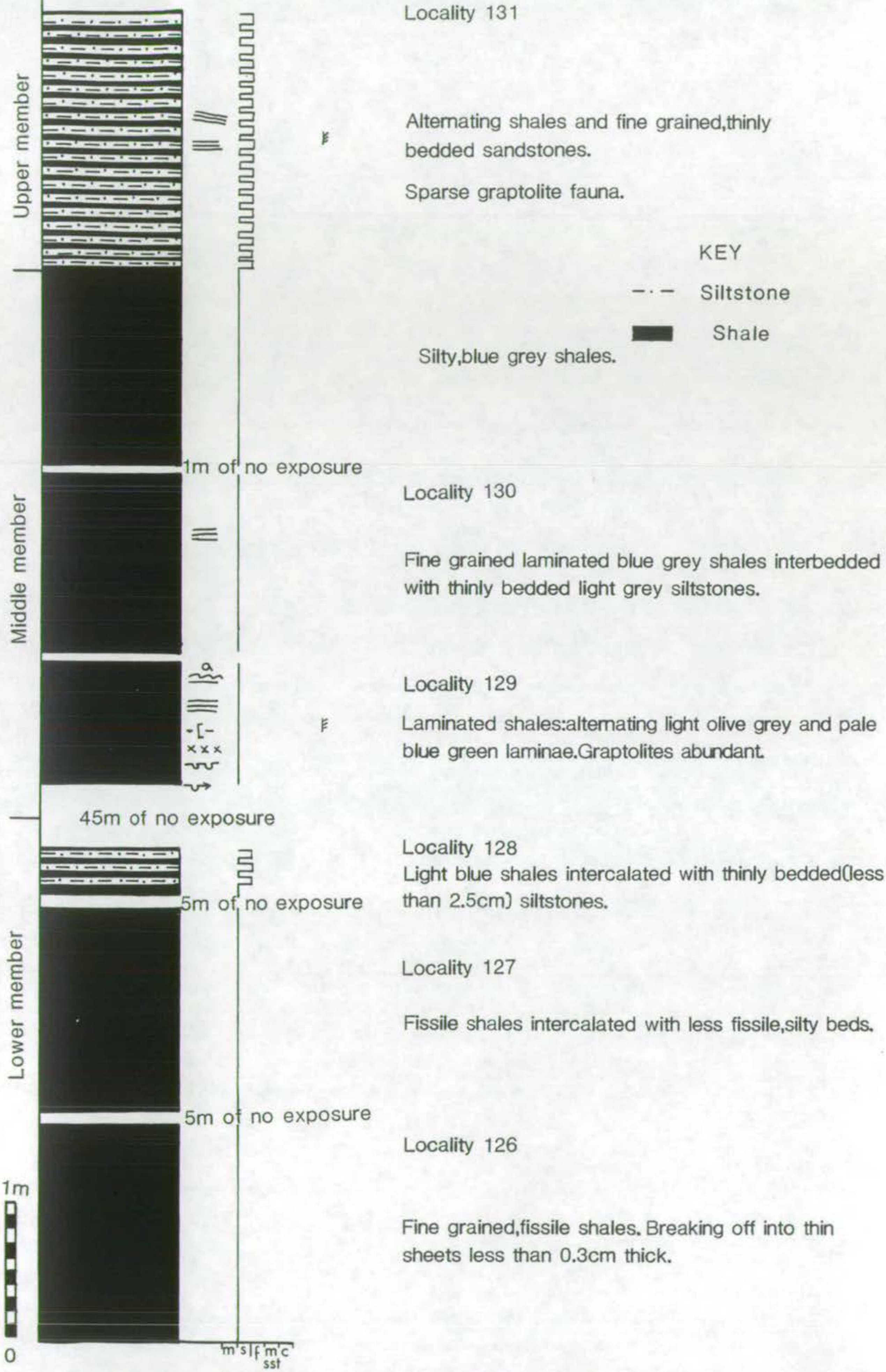
Due to the poor exposure, lack of obvious bedding and sedimentary structures in the fine-grained sandstone of the rest of the Newlands Formation, it can only be postulated that the sediments were rapidly dumped. During periods of quiescence or slow sedimentation the sub-stratum was burrowed and bioturbated. The combination of a calcareous epifauna and strongly bioturbated sediment (reworked biologically by abundant infauna) complies with the Aerobic zone in Byers' (1977) model of biofacies change in a stagnant basin, in which the water column was well oxygenated and the depth of sea water was relatively shallow.

2.2.5 Glenshalloch Shale Formation

Exposures in a small tributary stream, flowing perpendicular to the Baldrennan Burn, form the bases upon which the Glenshalloch Shale is subdivided (Fig. 2.12). The Formation comprises of a lower unfossiliferous shale member, a middle laminated banded shale and an upper member of shales interbedded with sandstones, estimated as 360m thick.

Near the base the fine-grained shales are faintly laminated. The clay minerals are very well aligned, increasing the fissility such that the shales break into sheets less than 0.3cm thick. Higher up in the section at locality 128 (NS 279042) the shales are intercalated with a few medium-grained (0.01mm) light blue coloured siltstones (Plate 1.7.3). Laminations in the siltstone are defined by the abundance of alterations of quartz rich and quartz poor horizons as are small scale faint cross-laminations, with an average height of 0.6cm. In addition some of the green coloured siltstones have brown flasers. Though the clay matrix does show some alignment the siltstones are less fissile, breaking into thin sheets less than 2cm thick.

At locality 129 (NS 281042), the middle member is represented by very fine-grained <0.01mm laminated fissile shales breaking into thin sheets less than 0.2cm in thickness (Plate 1.7.4 & 5). The bands of lamination are approximately 0.3 to 0.1cm thick and are caused by colour and grain size differences. Contacts viewed with the naked eye appear sharp. The light olive-grey coloured laminae are of slightly coarser grade (ranging between 0.09-0.01mm) yet slightly thinner, ranging from 0.1 to 0.2cm thick. Brown organic flasers and graptolite fragments are present. The pale blue-green laminae are slightly thicker, ranging from 0.1 to 1.0cm, are more fissile and finer grained (ranging 0.04-<0.01mm), and lack both the flasers and graptolitic fragments. Perhaps the most distinguishing features are the small load casts, flutes and tool marks developed on the soles of the beds (Plates 1.7.6 - 8 and 1.8.1 & 2). Load casts and flutes do not exceed 0.8cm diameter whilst very long slender groove



Fig(2.12) Stratigraphic section of the Glenshalloch Shale Formation.

marks are as long as 8cm, exhibiting a relief of 1mm. Generally the flutes are narrow and have fairly pointed noses.

Towards the top of the Formation, in the upper member, the laminated blue-grey shales (yielding only a sparse graptolite fauna) are interbedded with thickly-bedded (2-5cm thick) quartz-rich siltstones (Plate 1.8.3). Small-scale ripple cross-laminations (with heights of less than 1.5cm) at locality 129 (NS 281042), are accentuated by dark-brown oxide. These are asymmetrical, with a steep lee side and gentle stoss side, with a short wave-length (<1cm).

Gradually the sandstone ratio increases and at locality 145 (NS 283044), where many exposures are seen in the Baldrennan Burn, fine-grained thinly-bedded (less than 10cm bed thickness) light-grey sandstones are interbedded with fine-grained unfossiliferous shales (Plates 1.8.4 - 7). Extruding into the Glenshalloch Shales at locality 143 (NS 283044), a dolerite dyke is present (Plate 1.8.6).

Interpretation

The light-green unfossiliferous shales are interpreted as representing low velocity flows of turbid mud which deposited very slowly in layers over a long time period. These can be generated by storm waves on the shelf which mix up sediment to produce a turbid layer or, as in this case, are the result of the development of a dilute tail to a high density turbidity current. Typically they possess the suite of sedimentary structures on the soles of the beds which are associated with turbidites, and occasionally are very subtly cross-laminated.

Normally sole marks are caused by unequal loading or unstable density stratification (Pettijohn, 1975). Load casts, more properly known as load pockets, are somewhat irregular bulbous or mammillary features on the base of a sandstone bed that overlies shale. Though resembling flute casts in size and relief they differ in their irregularity and lack of symmetry and orientation. These structures are a product of unequal loading of the underlying hydroplastic mud and owe their origin to vertical re-adjustment, with the downward motion of the sand and compensatory upward movement of mud.

Current scour produces flutes which, upon becoming filled with sand and welded to the overlying sand bed, form flute casts. Flutes seem to have formed by eddy scours. Under particular current flow conditions a swarm of eddies develops which scour the underlying mud surface. Although the nose is usually the more prominent part of the flute, the greatest volume of deposition occurs in the tail of the flute indicating that as the nose portion of the flute lengthens, so the entire flute widens. The most recent classification of flutes is that of Dzulynski and Walton (1965) who recognise linguoid, triangular, elongate-symmetrical and bulbous types with shallow and deep varieties. Tanka (1970) made systematic observations, noting that flute shape did not appear to be related to bed thickness or grain size but that small flutes tend to be associated with thin beds and larger flutes with thicker beds. Furthermore he suggested that small flutes on thin beds represent currents of lower erosive power than those which formed larger flutes on thicker beds. However Pett and Walker (1971) believe that there is no relationship between flute depth and bed thickness. In agreement with their observations the flutes in the Glenshalloch Shale do show differences in morphology, coexisting on the same bed, and the reason proposed for these differences mainly involve fluctuations in turbulence and hence bed shear stress, differences in time of visitation and cessation of scouring, and differences in the capacity to erode the substrate. In addition there was no apparent downcurrent change in general flute morphology. According to Pett and Walker (1971) the narrow pointed flutes, seen in the Glenshalloch Shale, are associated with Tb and Tc turbidite beds and contrast markedly with the wider, more bulbous, coarser-grained flutes found on the soles of Ta beds. Apparently turbidity currents depositing Tb and Tc beds achieve very little bulk erosion of the substrate. Scouring at the nose of the current resulted in smaller, more pointed flutes and filling took place probably by tractional rolling of grains in the flute. With general bed load traction taking place, individual grains would be free to roll or skip relative to each other and hence the smaller traction tool marks tend to be associated with thinner finer beds.

The fissility in the Glenshalloch Shale is caused by the parallel alignment of the clay minerals (Ingram, 1953; O'Brien, 1970). Most of the theoretical work explaining the origin of the parallelism or conversely the lack of fissility in mudstones is purely sedimentological but the effects of infauna have been generally ignored. It is recognised that where normal marine conditions do not prevail, the burrowing infauna may be reduced in size and diversity or may even be absent, as can be seen in several Recent marine environments. For example, the sediments from the offshore basins of Southern California and from the continental slope of the Gulf of California lack an infauna (Emery, 1960; Hüllesemann and Emery, 1961; Emery and Hüllesemann 1962; Calvert, 1964, 1966; van Andel, 1964). In the particular case quoted this is ascribed to the Pacific oxygen minimum zone, but generally lack of infauna is a result of stagnation at the sediment-water interface. Furthermore the lack of infauna suggests that the original depositional structures, such as laminations, are preserved. Whilst studying two shale sequences in the Upper Devonian of New York State and Upper Cretaceous of the Western Interior, Byers (1974) recognised that fissility increases along a gradient of decreasing bioturbation. From his observations Byers concluded that fissility in unmetamorphosed azoic marine shales is due primarily to the original horizontal alignment of particles, but points out that it can only be preserved when burrowing infaunas are absent in the original mud. The original environment of deposition in the Glenshalloch Shale may likewise have been abiotic, the result of bottom stagnation under the stratified water column.

The darker coloured, generally structureless laminae represent the hemipelagic mud layer, the settling of finer fractions, in which the graptolites fragments sank down. Comparing the sediments with the classical Bouma sequence, these alternating laminae correlate with a Td-Te sequence, Facies G. Based on a large number of observations and published data, Walker (1967) summarised the characteristics of proximal and distal facies. He recognised the possibility of tracing lithological changes in a downcurrent direction and relating these changes to depositional environments both close to the source (proximal) and further away from the source (distal). In a sequence of turbiditic beds the following changes take place in downcurrent; sandstone-shale ratio, sandstone thickness, grain size and erosive features (amalgamated sandstones, channels) all decrease. For example scour marks such as flutes become fewer. Thus in terms of the source area, it is postulated that the Glenshalloch shales appear to represent distal turbidites. In turbidite fans however, turbidites of both proximal and distal aspect may be directly juxtaposed (Haner 1971) because they are laterally proximal and distal relative to channels. It is thus preferred to use the term 'thin-bedded turbidites' (Haner, 1971) for the Glenshalloch Shale.

Towards the top of the Glenshalloch Shale, the sandstone-shale ratio increases resulting in a coarsening, thickening upward sequence, which can be interpreted as Tb-Td-Te and Tc-Td-Te sequence. It appears that as the channel system prograded, more sediment was being deposited, so that a wedge of clastics advanced in an offshore direction.

2.2.6 Saugh Hill Grit Formation

The top of the Glenshalloch Shale is represented in Baldrennan Burn by alternating shales and thinly-bedded fine-grained siltstones, and within 10m (NS 283044) the base of the Upper Saugh Hill Grits, characterised by a pebbly sandstone, is exposed. Texturally, the pebbly sandstone is matrix-supported, consisting of small, fairly equant pebbles (less than 0.6cm in diameter) of sugar lump quartz are surrounded by a much finer-grained sandy light-brown coloured matrix.

Up section, the grain size decreases and the rest of the Formation consists of thickly bedded (bed thickness ranging from 1.30 to 1.0m thick) pale-brown coloured coarse- to medium-grained lithic arenites (0.6-0.4cm) (Plate 1.8.8). Lack of exposure hinders not only the accurate description of the Formation but also an estimation of Formation thickness. Cocks and Toghill (1973) infer a thickness of 290m and note the presence of inconspicious sole markings. No fossils were recovered but Freshney (1959) reports finding unidentifiable brachiopods at his locality 10.

Interpretation

The thickening upwards of the sequence as represented by the Glenshalloch Shale to the basal Upper Saugh Hill Pebbly Sandstone Formation is interpreted to represent another progradation of a channel on a submarine Fan.

The abrupt influx of coarser detrital grains indicates a slight rejuvenation in the hinterland and the development of another autocyclic erosional channel. This was short lived as the grain size rapidly decreases and the pebbly sandstone is less than 30m thick. Variation in the composition of the clasts reveals little because the channel feeder may have had a number of source areas supplying it via smaller distributary channels. The recorded sole markings (Cocks and Toghill, 1973) are possibly the products of turbidites.

2.2.7 Pencleuch Shale Formation

Only one exposure of the Pencleuch Shale was found, in a ditch (NS 29370543) 250m, 30^{o} east of Carscallan Cairn (Cocks and Toghill, 1973). The grey-brown shales are intercalated with siltstones, from which graptolites and brachiopods can be extracted. Unfortunately, the thickness of the formation cannot be calculated, due to the lack of exposure. Further excavations are required.

Interpretation

Owing to the lack of exposure, environmental interpretations of the Pencleuch Shale are very limited. It is plausible that the underlying Upper Saugh Hill Grits gradually fine up into the Shales which either: 1) records the decrease in the capacity of flow to carry detrital grains resulting in the settling of the finer fraction; or 2) is a result of deposition by fewer flows; or 3) indicates that the source area was only generating mud. The dark colour of the Shales draws comparison with the black graptolite shales of Moffat, suggesting euxinic conditions at the water-substratum interface and therefore the shales may have been deposited at some depth.

2.2.8 The Lower Camregan Grit Formation

A small overgrown and abandoned pit in Craigfin Wood (NS 29640540) is the only reported exposure of the Lower Camregan Grits. The underlying Pencleuch

There is a pronounced change in both the lithologies and faunas between the Pencleuch Shale and overlying Lower Camregan Grits. Furthermore Cocks and Toghill (1973) recognise a gap in the fossil record of most of the *sedgwickii* zone, since the graptolites in the Pencleuch Shale can be correlated with the *convolutus* zone, with only one recorded specimen of *Monograptus sedgwickii*, whereas the brachiopods recovered from the Lower Camregan Sandstones can be correlated with the very top of the *sedgwickii* zone (Cocks, 1971). Except in Penwhapple Burn where the junction between the Pencleuch Shale and overlying Lower Camregan Grit, is seen to be represented by the Lower Camregan Fault, it is not known if the stratigraphical break is repesented by a paraconformity or an unconformity.

2.3 GENERAL INTERPRETATION OF CRAIGHEAD SUCCESSION

The most striking large-scale sedimentological features in the succession at Craighead are four major depositional cycles.

1) the thinning-and fining-upwards sequence comprising of the Mulloch Hill Conglomerate, the Mulloch Hill Formation and Glenwells Shale.

2) the thinning-and fining-upwards sequence of the Newlands Conglomerate Member, Newlands Formation and Glenshalloch Shale.

3) the thickening-and coarsening-upwards sequence of the topmost of the Glenshalloch Shale and Upper Saugh Hill Grits.

4) the thinning-and fining-upwards sequence of the Upper Saugh Hill Grits into the Pencleuch Shale.

Commonly the cycles start off with conglomerates passing upwards through sandstones and siltstones into shales, representing the superposition of supra fan lobes that shifted laterally and built out on top of each other during mid-fan progradation.

In addition there is a gradual reduction in the coarsest detritus from the conglomerates, in that, at the base of the succession the coarsest clast size in the Mulloch Hill Conglomerate is 14cm, yet in the stratigraphically higher Newlands Conglomerate Member, the coarsest clast size is 7cm in diameter and in the Upper Saugh Hill Grits the pebbles are only 0.5cm in diameter. Not only does this reflect the gradual increase in distance from the source area with time, but also it may suggest the gradual erosion of the source area from which the detritus came.

Plates 1.1 - 1.8 (Chapter 2)

PLATE 1.1

MULLOCH HILL CONGLOMERATE FORMATION (LOCALITY 13)

Figures

1. Side profile of locality 13, showing the Mulloch Hill Conglomerate Formation. The harder more resistant sandstone beds stick out from the pebble to cobble conglomerate units. Scale: hammer 33 cm.

2. Poorly-sorted, clast supported cobble conglomerate. The clast shape is dominantly elongate-tabulate, of low sphericity. Scale: hammer 33 cm.

3. Poorly-sorted, clast-supported cobble conglomerate. Clasts are dominantly well-rounded. Scale: hammer 33 cm.

4. Cut slab of conglomerate. Peeble clasts composed of basic to acidic igneous rocks, quartz and red jasper bound in a matrix of clay and sand. Pebble to pebble contacts show evidence of compaction. Scale: bar cm.

5. Conglomerate-sandstone contacts are commonly gradational, traced through 5 to 10 cms. Scale: coin 2.8 cm.

6. Gradational contact between conglomerate and the overlying coarse-grained sandstone. Scale: coin 2.8 cm.

7. Gradational contact between conglomerate and the overlying coarse-grained sandstone. Rounded pebble- and grit-sized clasts. Grain size fines upwards. Scale: bar cms.

PLATE 1.1

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Plate 1.2

MULLOCH HILL CONGLOMERATE FORMATION (LOCALITY 13)

Figures

1. Very coarse-grained sandstone, in which pebble-sized clasts are seen floating in the sandstone showing preferred orientation parallel to bedding. Clast size decreases gradually upwards. Scale: coin 2.8 cm.

2. Poorly-sorted, clast-supported cobble conglomerate overlain by a pebbly coarse-grained sandstone, a matrix-supported pebble conglomerate and a cross bedded coarse-grained sandstone. Scale: at base, hammer 33 cm, and at top, coin 2.8 cm.

3. Low-angle cross-stratification in coarse-grained sandstone. Subtle variations in grain size are accentuated by differential weathering. Scale: coin 2.8 cm.

4. Similarly faint laminations are detected by slight grain size differences in the coarse-grained sandstone. The succeeding coarser-grained sandstone displays an erosional base, truncating the underlying faint laminations.
Scale: coin 2.8 cm.

5. Towards the flanks of locality 13, parallel-laminated, thinly-bedded coarse-grained sandstones are occasionally overlain by very poorly-sorted, pebble to cobble conglomerates and coarse-grained sandstones which exhibit trough cross-bedding. Scale: coin 2.8 cm.

6. General view of previous photograph, showing pebble to cobble conglomerates interbedded with parallel-laminated and crossbedded sandstones. Scale: hammer 33 cm.

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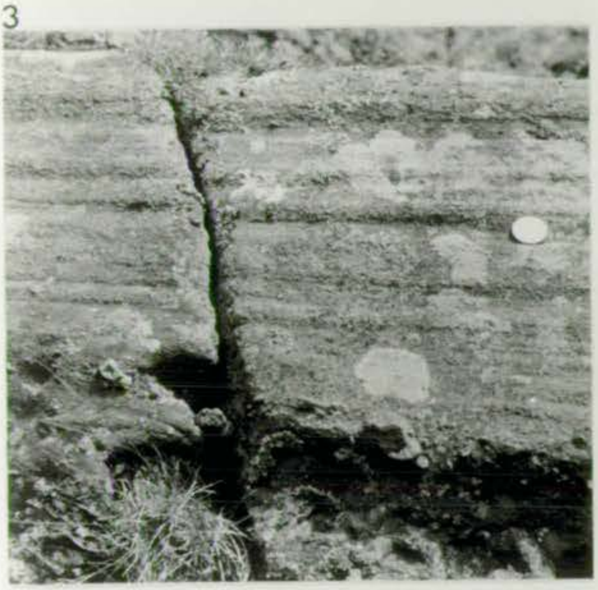

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Plate 1.3

MULLOCH HILL CONGLOMERATE FORMATION (LOCALITY 13)

Figures

1. Locality 1(a), very thinly-bedded medium-grained sandstones, occurring in the middle of the Mulloch Hill Conglomerate. Fossils are rare including brachiopod fragments and crinoid ossicles. These are overlain by poorly-sorted pebble conglomerates (b) (locality 4).

2. Close up of the thinly-bedded sandstone of locality 1 (1a). Infrequently there are concentrations of well-rounded, elongate to tabulate shaped pebbles. Scale: coin 2.8 cm.

MULLOCH HILL FORMATION

3. Thinly- and medium-bedded, fine-grained dark brown coloured sandstones, (locality 19). Scale: hammer 33 cm.

4. Close up of locality 19, showing characteristic weathering of the sandstones in which the sandstones often possess undulating upper surfaces. Arrow points to fossil bands up to 50 cm long, and 4 cm thick, yielding disarticulated brachiopods and loose crinoid ossicles. Scale: hammer 33 cm.

5. Thinly-bedded fine-grained sandstones of locality 74 weathering in the same manner. Scale: hammer 33 cm.

6. Close up of locality 74. Arrow points to a fossil horizon which is up to 8 cm thick and can be traced for over a meter. Scale: hammer 33 cm.

7. Close up of fossil horizon seen in previous photograph. Fossils include disarticulated brachiopods, crinoid ossicles and a few solitary coral. Cavities occur where the fossils have been weathered, yet when freshly broken, the fossils are calcified. Scale: coin 2.8 cm.

8. Fine-grained light olive-grey coloured sandstones weathering to a yellow-brown colour. Tend to weather in a blocky manner. Fossil horizons are abundant (locality 32).
Scale: hammer 33 cm.

PLATE 1.3

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Plate 1.4

MULLOCH HILL FORMATION

Figures

1. Locality 41, medium- to thickly-bedded very fine-grained sandstones. Characteristically they weather a moderate brown colour, but internally they are grey-red-purple in colour. Scale: hammer 33 cm.

2. Siltstone overlain by a medium-grained sandstone in which fossils occur at the base. This fossil horizon is up to 7 cm thick and can be traced for just over a metre. Fossils include partially calcified disarticulated brachiopods, crinoid ossicles and solitary corals (locality 41). Scale: coin 2.8 cm

3. Rough Neuk Quarry, locality 89, constitutes the upper member of the Mulloch Hill Formation. The sediments are comprised of very fine-grained dusky yellow-green coloured sandstones, siltstone and towards the top, paper shales are intercalated with fine-grained sandstones. Scale: hammer 33 cm.

4. Fine-grained sandstones fine upwards into siltstones and paper shales (locality 89). Scale: hammer 33 cm.

5. Towards the top of the Quarry fine-grained sandstones are interbedded with pale-brown coloured paper shales. Scale: hammer 33 cm.

6. Close up of photograph 3 (locality 89), where the Starfish bed is exposed. Distinctively the siltstone weathers in a blocky manner often possessing convex upper surfaces. Scale: hammer 33 cm.

7. Close up of the Starfish bed, containing dendroid fragments, an articulated complete crinoid and mud flakes. Scale: coin 2.8 cm.

PLATE 1.4

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Plate 1.5

GLENWELLS SHALE FORMATION

Figures

1. General view of the gully behind Kirkhill and the topographic rise in which the Newlands Conglomerate is exposed.

2. Exposure of Glenwells Siltstones occurring on the flanks of the gully, locality 53. Strangely, the exposure shows the effects of exfoliation. Scale: hammer 33 cm.

3. Due to the poor quality of the exposure and effects of weathering, bedding is generally obscured in the Glenwells siltstones (locality 54). Scale: hammer 33 cm.

4. Siltstones possibly interbedded with slightly finer-grained layers. The siltstones are dark grey coloured weathering to a yellow-brown colour (locality 53). Scale: hammer 33 cm.

5. Perfect example of spheroidal exfoliation in the Glenwells siltstones (locality 52). Scale: coin 2.8 cm.

6. Large exposure of the Glenwells mudstone, occurring in the Glenwells Burn (locality 84). Although very fine-grained, they are slightly silty, and are non-fissile. Scale: hammer 33 cm.

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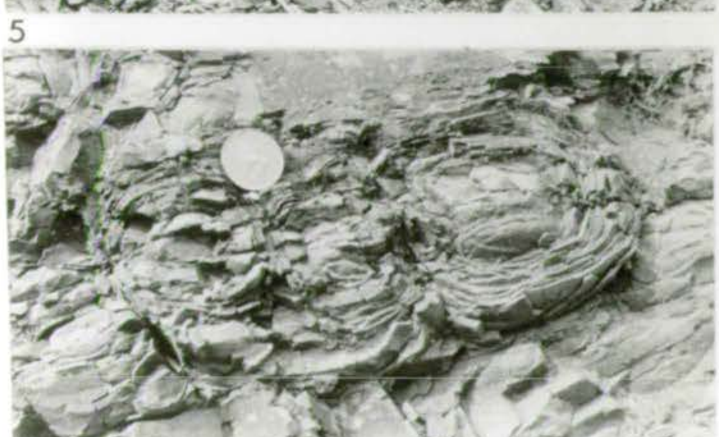

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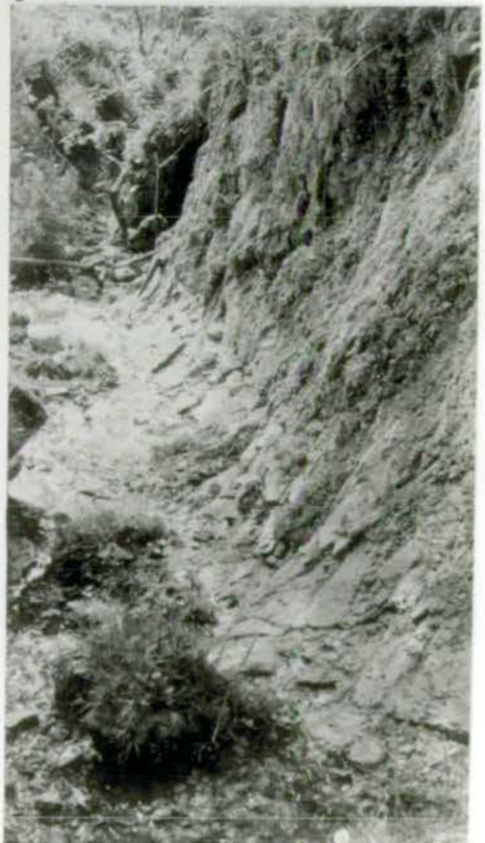


Plate 1.6

GLENWELLS SHALE FORMATION

Figures

1. Glenwells siltstones, occurring at the base of the Newlands Conglomerate at locality 93 (see following photograph 2, indicated by an arrow). Scale: hammer 33 cm.

2. Low topographic rise, locality 55 (close up of Figure 1.5 1) composed of the Newlands conglomerates and sandstones. Characteristically the geometry of the exposure is crescent shaped. The conglomerate is underlain by the Glenwells siltstones (see arrow). Scale: sheep, and hammer 33 cm.

3. Cut slab of Glenwells siltstones from locality 93 (Figure 1) revealing a grey-orange coloured quartz arenite. Along lines of weakness haematite has been precipitated staining the rock pale brown. Scale: bar cms.

4. Cut slab of Newlands conglomerate. Generally the conglomerate is matrix-supported, containing pebble-sized clasts, of quartz, jasper and chert. Scale: bar cms.

5. Clast-supported, poorly-sorted pebble conglomerate, bound in a sandy matrix. No preferred orientation of the pebbles is obvious. Scale: coin 2.8 cm.

6. Poorly-sorted matrix-supported pebble conglomerate. In places the conglomerate and sandstones are stained a pale brown colour, associated with haematite. Scale: hammer 33 cm.

7. Coarse-grained sandstone lens occurring at the base of locality 55. Scale: hammer 33 cm.

PLATE 1.6

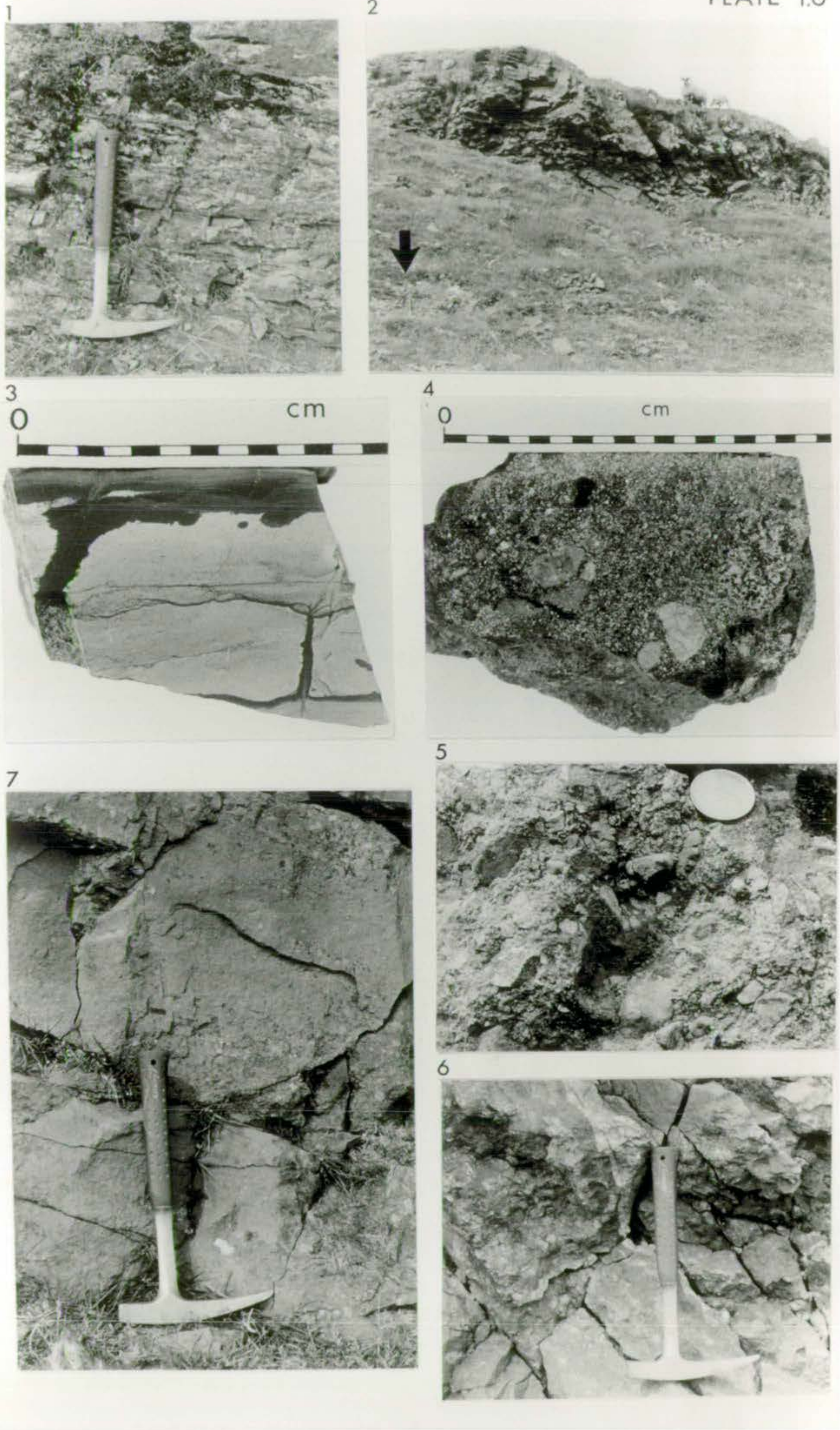


Plate 1.7

NEWLANDS FORMATION

Figures

1. Small exposure (locality 125) of Newlands Formation. Scale: hammer 33 cm.

2. The largest exposure of Newlands Formation occurs beside a small burn, northeast of Newlands Farm. Bedding is generally obscured and fossils are abundant (locality 124). Scale: hammer 33 cm.

GLENSHALLOCH FORMATION

3. Small exposure (locality 126) of the lower member of the Glenshalloch Formation, composed of light blue coloured shales. Scale: hammer 33 cm.

4. Stratigraphically higher, the Glenshalloch Formation is composed of laminated shales (locality 129) tending to break off as thin plates up to 0.2 cm thick. Here graptolites are abundant. Scale: hammer 33 cm.

5. Close up of the laminated shales from locality 129. Laminations are up to 0.2 cm thick and are defined by subtle grain size differences and variations in colour, changing from light olive-grey to blue-green. Scale: coin 2.8 cm.

6. Very subtle asymmetric ripples occurring in the Glenshalloch Formation (locality 129). Scale: bar

7. Tool mark occurring on the sole of a shale laminae (locality 129). Scale: bar cms.

8. Tool mark occurring on the sole of a shale laminae (locality 129). Scale: bar cms.

PLATE 1.7

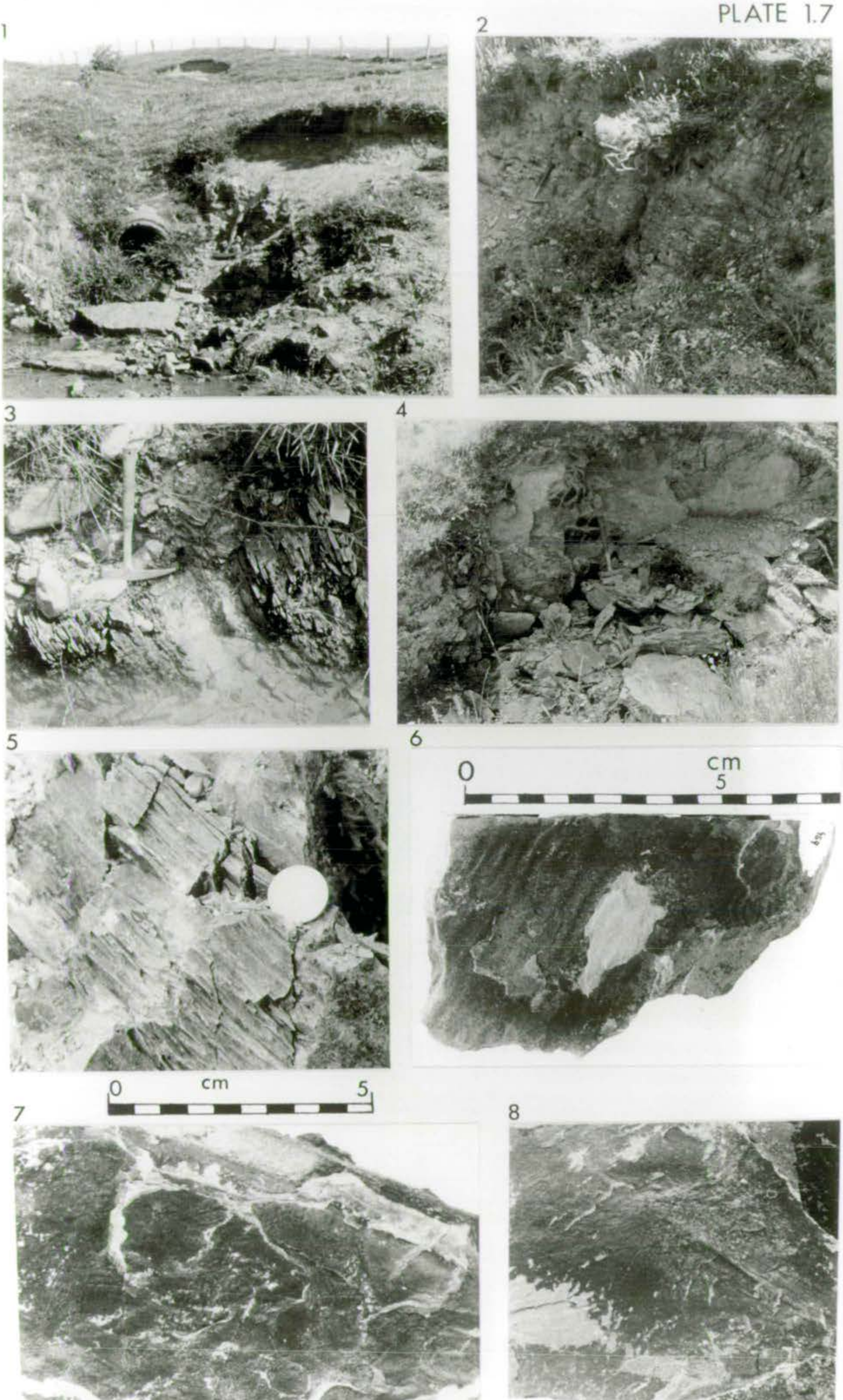


Plate 1.8

GLENSHALLOCH SHALE FORMATION

Figures

1. Small flute on the sole of the Glenshalloch Shale (locality 129). Scale: bar cms.

2. Very faint flute casts on the sole of the Glenshalloch Formation (locality 129). Scale: bar cms.

3. Towards the top of the Glenshalloch Formation the shales are interbedded with thinly-bedded light grey coloured siltstones. Very faint cross-bedding can be seen in the siltstones. Graptolites are rare (locality 130). Scale: hammer 33 cm.

4. Blue-grey coloured shales alternating with slightly thicker-bedded siltstones, denoting the higher parts of the Glenshalloch Formation. Throughout the Baldrennan Burn, the Glenshalloch Formation is folded. Here the beds are dipping almost vertically (locality 143). Scale: hammer 33 cm.

5. Close up of alternating shales and siltstones of the Glenshalloch Formation, locality 143. Scale: hammer 44 cm.

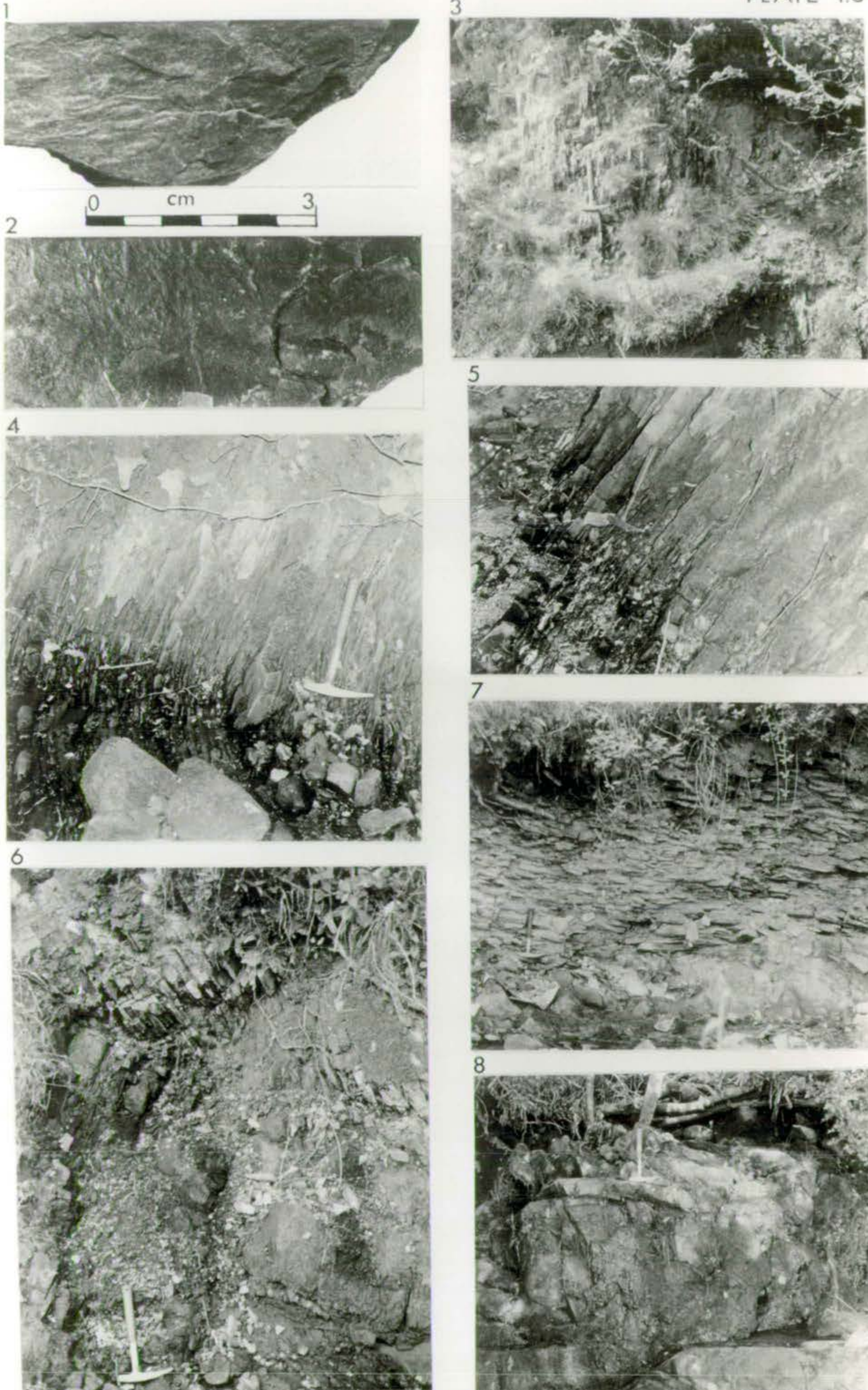
6. Gradually the sandstone:shale ratio decreases such that the upper sequence of the Glenshalloch Formation is composed of thinly bedded siltstones interbedded with shales. At locality 144 the siltstones are intruded by a small dolerite dyke trending northeast-southwest. Scale: hammer 33 cm.

7. Thinly-bedded Glenshalloch siltstones dipping horizontally. Graptolites are scarce (locality 145). Scale: hammer 33 cm.

UPPER SAUGH HILL GRIT FORMATION

8. Large exposure of the Upper Saugh Hill Grits in the Baldrennan Burn (locality 146). The coarse-grained light brown coloured sandstones are very thickly-bedded. Scale: hammer 33 cm.

PLATE 1.8



CHAPTER 3

3. THE GEOLOGY OF THE SILURIAN ROCKS AT THE HAVEN AND WOODLAND POINT, GIRVAN COAST

3.1 INTRODUCTION

Silurian rocks are also exposed south of Girvan in the area of Woodland Bay (Fig. 3.1) specifically at the Haven; Craigskelly (NS 1776, NS 9603), the Horse Rock (NS 1794, NS 9613) and the Cow Rock (NS 1799, NS 9618); and at Woodland Point (NS 1692, NS 9530) (Fig. 3.2). A number of small craggy peninsulas and islands form the main exposures. Contrasting with the more easily eroded Ordovician (Ardmillan beds), the hard and intractable nature of these Silurian strata produces a line of reefs which rise up boldly out of the deep water, and form a series of fringes along the seaward edge of the platform. During high tide, a line of long and narrow islands protects the platform, landwards of which the Ardmillan Series is drowned by less agitated waters. Outcrop numbers, in the text, refer to those plotted on the geological map (Figs. 3.1 and 3.2*). Since these Silurian exposures occur as isolated islands, it is very difficult to trace geological boundaries. In the illustrated geological maps, a solid line represents an exposed geological boundary whilst a short broken line indicates a calculated or inferred boundary. The Formation boundaries have been drawn with little variations in lateral thickness (Figs. 3.3 and 3.4). In addition at the Haven, locality 208, the Craigskelly Conglomerate is dissected by approximately five faults, and the resulting displacement is depicted in Fig. 3.6.

3.1.1 Ordovician-Silurian Junction

At the coastal locality 208, (NS 179962), there is a marked contrast between the underlying Shalloch Formation (Ordovician) and the overlying Craigskelly Conglomerate. The Shalloch Formation is characterised by thinly-bedded (0.20-0.30cm) pale-grey coloured, medium-grained sandstones interbedded with grey to black coloured fissile shales, while the Craigskelly Conglomerate, juxtaposed upon it, consists of pebble to cobble conglomerates. The actual contact, seen only at low tide, appears sharp and planar. Grading, in the sandstones and load structures on the sole of the Shalloch Formation (Ordovician), indicates younging in a seawards direction to the northwest, and similarly the Craigskelly Conglomerate youngs seawards. The underlying Shalloch Hill

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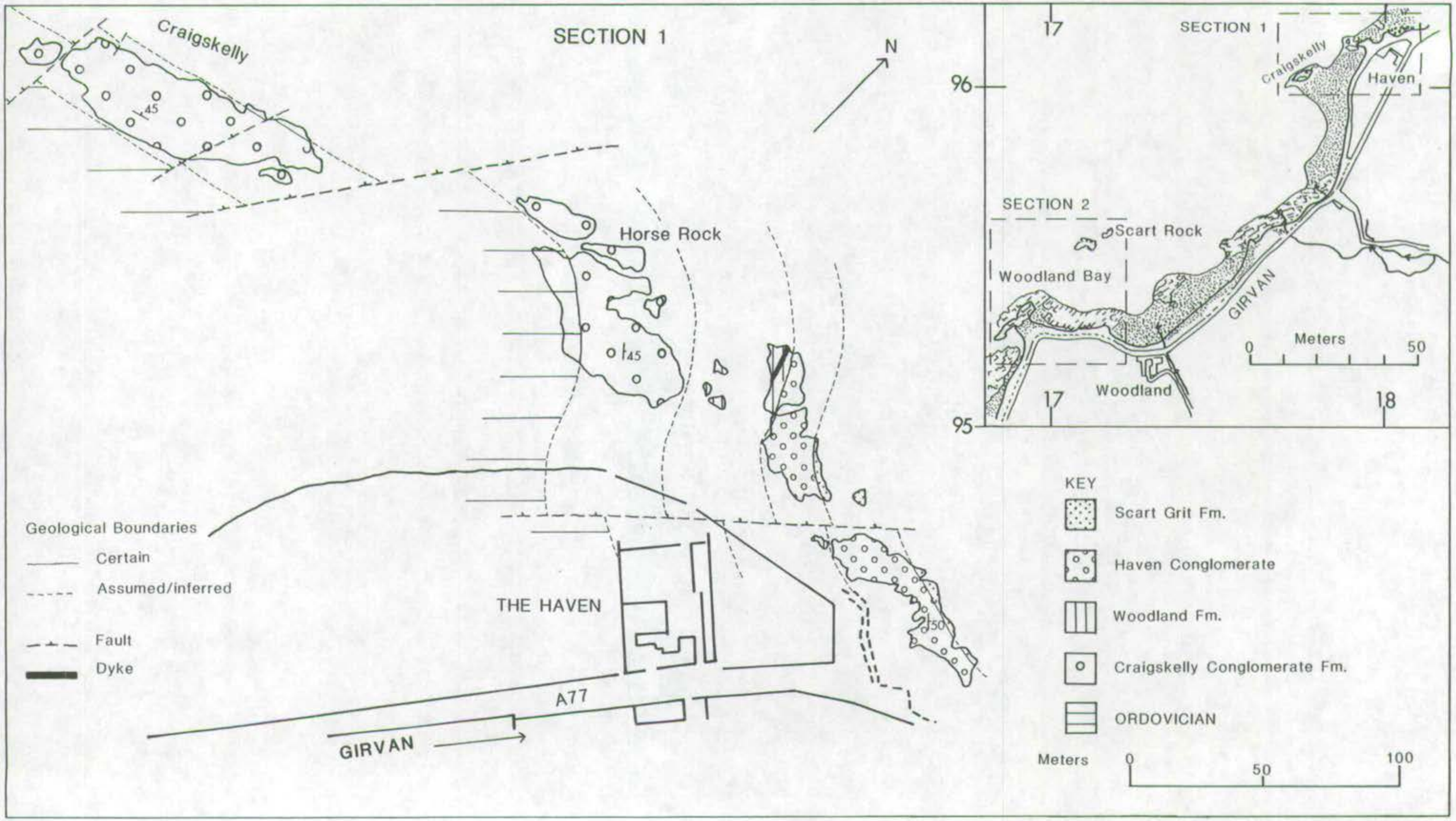
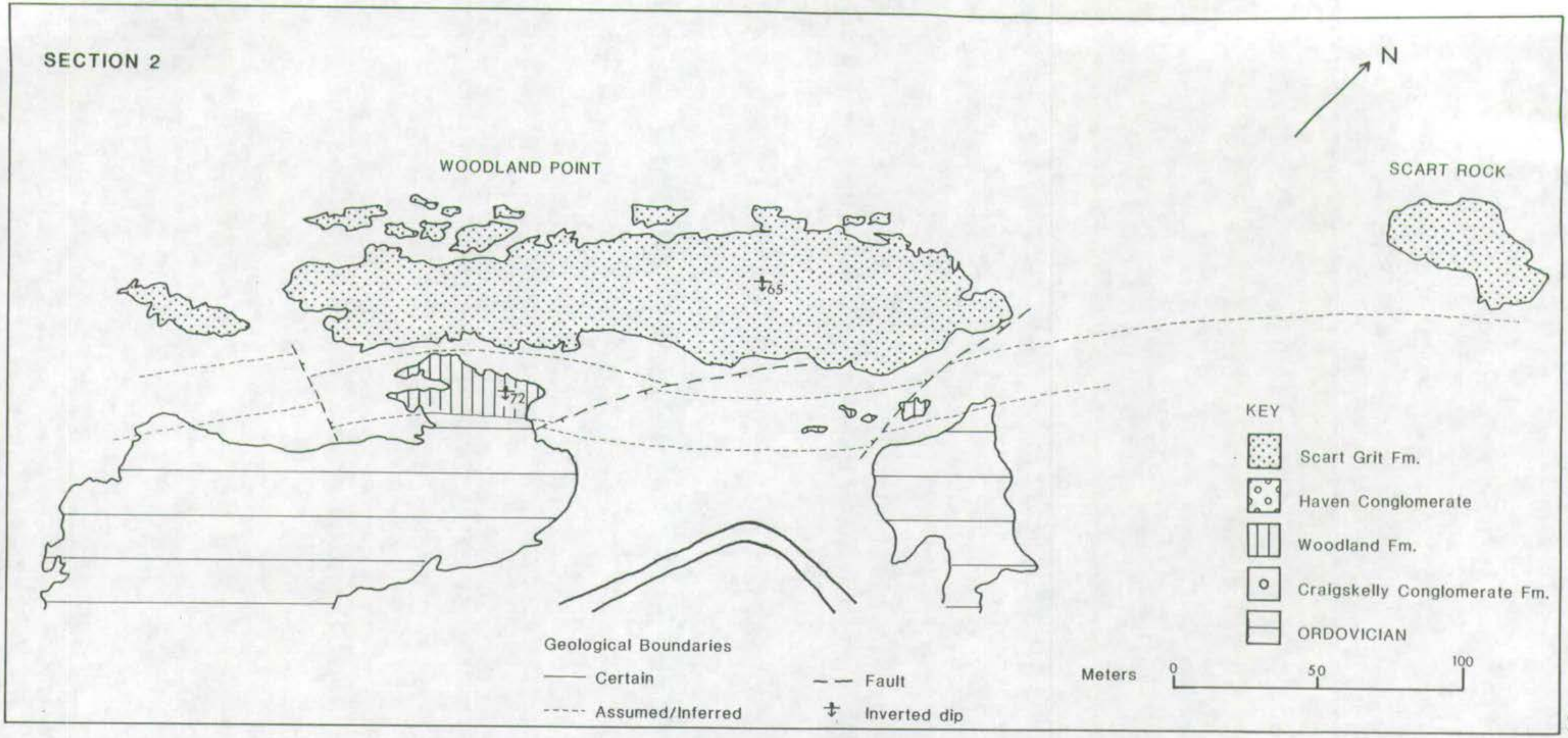
*Fig. (3.1) and (3.2) Large scale geology maps of the Coastal Sections. Maps in the back pocket.



Fig(3.3) Geological map of The Haven (modified from Cocks and Toghill 1973).



Fig(3.4) Geological map of Woodland Point (modified from Cocks and Toghill 1973).

Formation is intensely folded whereas the conglomerates are unaffected and there is no evidence of a fault contact since slickensides and a fault gangue are absent. It is clearly seen that the base of the Craigskelly Conglomerate unconformably overlies the Shalloch Formation.

Further south, on Woodland Point, the stratigraphically higher Woodland Formation unconformably overlies the Shalloch Formation (Harper, 1988).

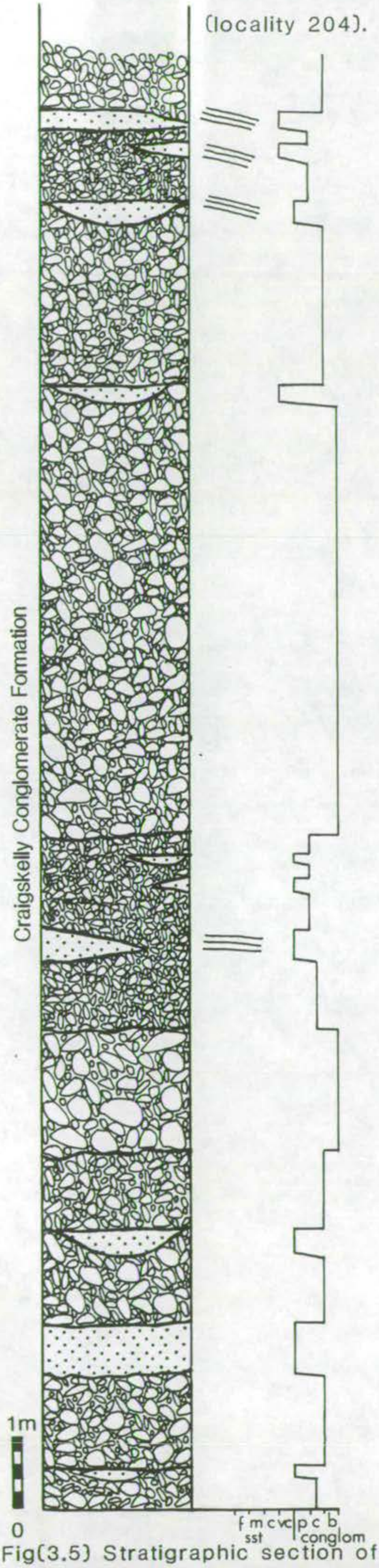
3.2 THE GEOLOGY OF THE COASTAL SECTIONS

3.2.1. Craigskelly Conglomerate Formation

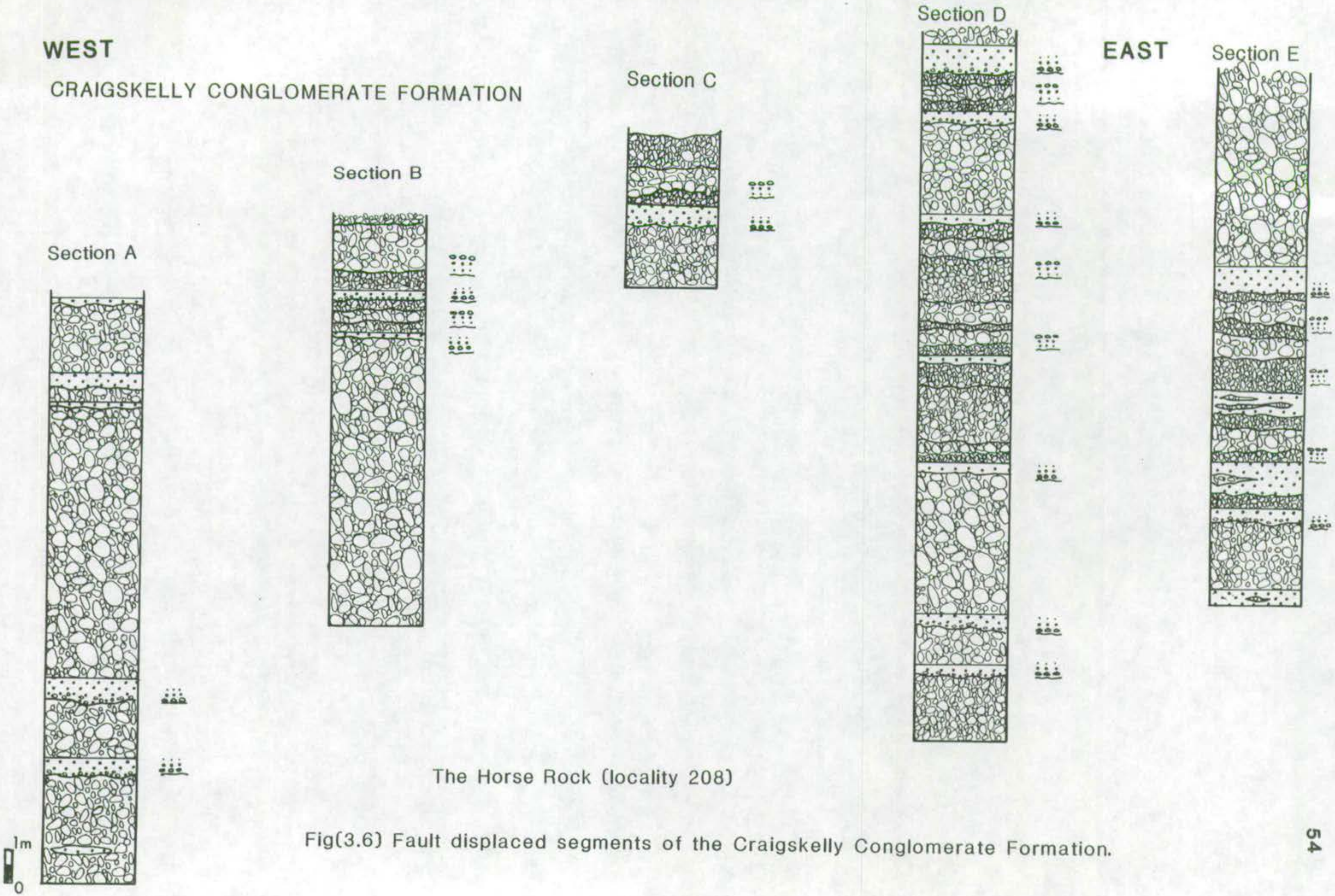
The Craigskelly Conglomerate is exposed in two areas (Fig. 3.3). The first is Craigskelly (locality 204, NS 178961) where it forms a long mound-like boss (c.100m by 30m) at high water, which at low tide is connected with the shore by a sandy beach (Plate 2.1.1 and 2.1.2). The second is at the Haven (locality 208, NS 178961) where the conglomerate forms a rugged low-lying boss, the Horse Rock, the most northerly part of the protecting fringe during high tide (Plate 2.1.3 and 2.1.4). Formation thickness is approximately 38m.

The conglomerate is very thickly bedded with the beds reaching up to 8m thick (Fig. 3.5), yet with an average thickness of 2.26m. Despite their low sphericity, the clasts are very well rounded, yet poorly sorted with clasts ranging from 2 to 30cm diameter (Plate 2.1.5). The assemblage of clasts include: acidic igneous and basic rocks, low- to high-grade metamorphics, mud clasts and reworked conglomerates (Plate 2.1.6). In most of the conglomerates the clasts appear to show no preferred orientation. Only in unit 1 at locality 204, a single surface displayed a convincing imbrication (Plate 2.1.7). Accounting for less than 10% of the rock, the matrix appears to consist of sand-sized particles and generally the conglomerate exhibits a clast-supported texture. Grading and stratification are lacking at Craigskelly, but an evident example of reverse grading is developed at locality 208 (Fig. 3.6), in which the larger clasts are found in the top third of the bed.

Regularly the conglomerates are interbedded with very coarse-grained lithic arenites of greyish-olive-green colour (Plate 2.1.8). Maximum matrix grain-size is approximately 0.1cm. Individual beds vary laterally in thickness and though individual units are traceable for up to 50m, they eventually thin out. Overall, bed thickness ranges from 0.22 to 2.20m (Plate 2.2.2). The base of the sandstone units are not planar, and pebbles from the underlying conglomerate sometimes protrude into the sandstone bases. When closely inspected, the top of the underlying conglomerate bed fines upwards over a distance of 5-10cm into the sandstone. On the other hand, the tops of the sandstones can be gradational or sharp (Plate 2.2.3). Sedimentary structures are limited to very low



Fig(3.5) Stratigraphic section of the Craigskelly Conglomerate Formation



Fig(3.6) Fault displaced segments of the Craigskelly Conglomerate Formation.

angle cross-bedding (Plate 2.2.1). Among the lower beds a few small pebbles up to 0.8cm in diameter are present. Though some are aligned with their long axis parallel to bedding, most of the pebbles exhibit a fairly random orientation.

At locality 208, the sandstones show normal and reverse grading (Plate 2.2.3). Over a distance of between 4 to 8cm there is a gradational transition from conglomerate- to pebbly-sandstone, in which the maximum pebble size is 2.5cm diameter, to a coarse-grained sandstone composed of grains less than 0.4cm (Plate 2.2.4). Similarly the sandstone units are faintly laminated with some floating pebbles (less than 2.0cm diameter) occasionally aligned with their long axis parallel to bedding. These small pebbles tend to be elongate to tabulate in shape, subrounded to subangular and vary in size from 0.4 to 1.9cm. Moreover, thin pebble concentrations occur within the sandstones but these are laterally discontinuous traced for less than 0.40m (Plate 2.2.5).

Approximately in the middle of both the Craigskelly and the Horse Rock exposures there are a few light blue-grey coloured shale clasts incorporated into a few conglomerate beds. Some have retained their original clast outline whilst others have been completely deformed by compaction and subsequently flow around other clasts, almost resembling a muddy matrix (Plate 2.2.6).

Interpretation

The Craigskelly Conglomerates are interpreted as having been deposited by a series of sediment gravity flows. The mechanics of sediment flows have been reviewed by Middleton (1966, 1967, 1969, 1970) Middleton and Hampton (1973, 1976), Nardin et al. (1979) and Lowe (1979). Middleton and Hampton (1973, 1976) subdivided sediment flows into four end-member flow types based on the mechanics by which the larger transported grains are supported above the bed. More recently Lowe (1976) and Nardin et al. (1979) have suggested a classification and nomenclature based upon rheology and partial support mechanisms.

The Craigskelly Conglomerates were deposited by debris flows (see Chapter 2), and were formed progressively from the base upwards. Debris flows deposit sediment when the applied shear stress drops below the yield strength of the moving material. The flow freezes inwards en masse (Johnson, 1970) as a consequence of frictional grain resistance and/or cohesive grain interactions. This accounts for the poor development of bedding and lack of sorting in the conglomerates.

Observations of sediment flow deposits, especially those of Walker (1975, 1977, 1978) and experiments of sediment transport and deposition (Bagnold, 1954; Middleton, 1967; Shook et al. 1968) indicate that deposition of sediment from turbidity currents must be treated in terms of several grain-size populations. It is thought that individual particle groups within the same flow are commonly held above the bed by a different support mechanism and may be deposited during discrete sedimentation waves. Lowe (1982) has recognised three main particle grain-size populations, namely: 1) clay, silt, fine- to medium-grained, in which clasts are maintained in suspension by fluid turbulence. These are commonly associated with low density flows in which the sediment support is largely independent of particle concentration; 2) coarse-grained sand to small pebble sized gravel, which can be supported by the combined effects of both turbulence and hindered settling. The latter results from grain concentration and from buoyant lift, provided by the mixture of water and finer-grained sediment, and finally; 3) pebble- and cobble-sized clasts supported by the combined effects of fluid turbulence, hindered settling, matrix buoyant lift and dispersive pressure resulting from grain collision. Grain size populations 2 and 3 are associated with high density flows, in which particle support is dependent on concentration-related effects. High density currents were first proposed by Kuenen (1950, 1951) and have been further subdivided by Lowe (1982) into sandy flows dominated by population 2 grains and gravelly flows containing population 3 grains.

Accordingly, the Craigskelly Conglomerates are related to gravelly flows containing population 3 grains, supported in large parts by dispersive pressure and matrix buoyant lift and were deposited by high density turbidity currents. Because of the presence of grains belonging to populations 1, 2 and 3, deposition often occurred as a series of discrete sedimentation waves as the flow decelerated and individual grain populations could no longer be maintained in transport. Each sedimentation wave tended to show increasing turbulence and accelerating sedimentation rate as it evolved, passing from an initial stage of traction sedimentation to one of mixed frictional freezing and suspension sedimentation within traction carpets, to a final stage of direct suspension sedimentation (Fig. 3.7). At locality 208 (Fig. 3.8), the conglomerates include a basal inversely-graded traction carpet layer overlain by a normally-graded suspension sedimentation unit. This correlates with the inversely to normally-graded conglomerate facies of Walker (1975, 1977) and with the basal conglomeratic layers I, II, III of Aalto (1976). The very coarse-grained conglomerates were probably transported near the bed within a highly concentrated traction carpet (Walker, 1975, 1977; Aalto, 1976) and in suspension in the lower part of the turbulent flow. Once the flow velocity dropped below that necessary to maintain the dispersive pressure in the traction carpet the cobbles were immediately deposited. The traction carpet froze and then suspension sedimentation commenced (Walker, 1975, 1977). The sharp gradational boundary between the conglomerate and sandstone represents the transition from traction to suspension sedimentation when the finer particles settled. It is important to note that deposition of the population 2 grains often occurs independently of population 3, because the sand-sized grains are supported by flow turbulence and hindered settling, and not

Fig. 3.7 Origin of traction carpet.

A) Basal part of high-density flow shows development ofinversely graded zone. V represents the generalised velocity profile.

B) Fallout from suspension increases clast concentration in basal layer and results in the formation of traction carpet, in which grains are fully supported by dispersive pressure.

C) Continued fallout from suspension loads the traction carpet, and causes freezing.

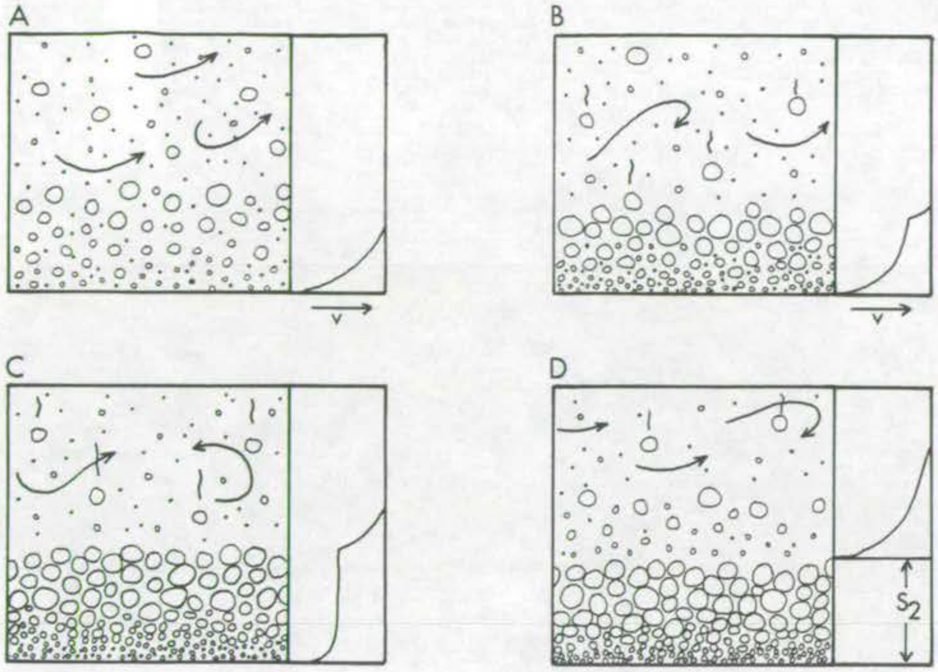
D) Final freezing of the traction carpet results in the formation of a new inversely graded basal flow layer, above the deposit. Thereafter the process repeats itself (from Lowe, 1979).

Fig. 3.8 Ideal sequence of divisions deposited by a single high density turbidity current declining through discrete gravelly and sedimentation waves.

Abbreviations as follows:

R_2 = inversely graded gravel layer; R_3 = normally graded gravel layer; S = sandy high density turbidity current; S_1 = division showing traction carpet structures, generally plane laminations and cross stratification; S_2 = division containing thin horizontal layers showing inverse grading; S_3 = division, may be structureless or normally graded, and commonly contains water-escape features (from Lowe, 1979).

Fig. 3.9 Complex sedimentation unit deposited by surging sandy high-density turbidity currents. Tt = Turbidite divisions (from Lowe, 1979).



Fig(3.7) Origin of a traction carpet (after Lowe,1979).

FIGURE 3.8

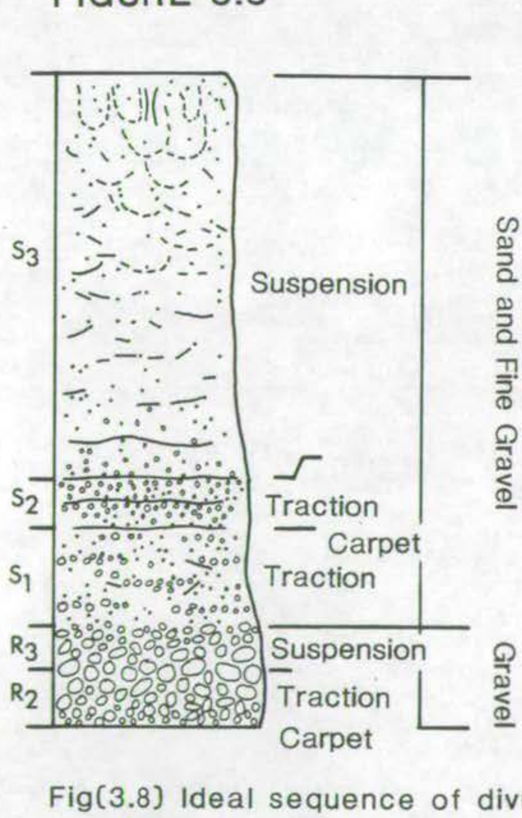
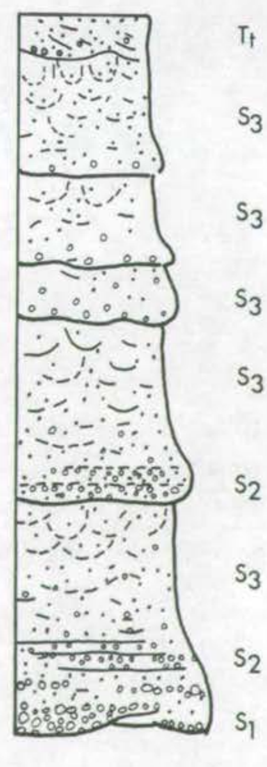


FIGURE 3.9



Fig(3.8) Ideal sequence of divisions deposited by a single high density turbidity current (after Lowe,1979).

Fig(3.9) Complex sedimentation unit by sandy high density turbidity current (after Lowe,1979).

dispersive pressure (Lowe, 1982). Following deposition of the coarser gravel the sedimentation history is that of a sandy, high-density turbidity current. The Craigskelly sandstones interbedded with the conglomerates are interpreted to be the products of these slightly unsteady but fully turbulent sandy, high-density turbidity currents. As with bedforms developed beneath low density flows, plane beds and dune-like features may have formed by the interaction of flow on the sandstone beds (Smith, 1955; Newitt et al. 1955; Sinclair, 1962; Govier and Aziz, 1972) thus exhibiting flat laminations. The pebble concentrations in the sandstone of locality 208 which are laterally not extensive represent pulses in the high density currents and were formed by the development of an inversely-graded zone similar to the process discussed above.

Although both of the conglomerates, at Craigskelly and the Haven, were deposited by the same genetic flow mechanisms there are slight variations in the development of grading. At Craigskelly reverse grading is less common and the sediments show normal grading. Reverse and normal grading are related to rates of deceleration and sediment concentration in individual flows. Since individual flows can not be traced, there is no reason to assume that the Craigskelly conglomerates and conglomerates at the Haven, would have had similar internal structures.

Each separate flow is assumed to be related to periodic uplift of the hinterland, providing an influx of very large boulders and cobbles or leading to very large sheet floods. The presence of laminated sandstones, and the gradational tops of the conglomerates commonly associated with fairly fluidised flows, indicates that conditions were sub-aqueous. Superficially the Craigskelly Conglomerates resemble the Mulloch Hill Conglomerates from Craighead in that both display conglomerates interbedded with sandstones which were deposited by debris flows and high density turbidity currents. The Craigskelly Conglomerate is also interpreted as having accumulated in a submarine fan, and these conglomerates (characteristic of Facies A normal- and reverse-graded conglomerates) probably were deposited in the inner fan. This fan was similarly situated along a newly inaugurated fault, and periodic fault movement would have provided the very large boulders and cobbles.

Since: 1) the Craigskelly Conglomerate is slightly younger than the Mulloch Hill Conglomerate (see Chapter 1); 2) there is a slight difference in the pebble to cobble clast composition in the two Formations and 3) the two Formations are at present physically separated by approximately 12km, it is here suggested that the Craigskelly Conglomerate accumulated in a different depositional area and therefore the Craighead Inlier Sequence and the Coastal sequences each represent separate fan systems.

Towards the top of the Formation the reduction in clast size is most likely associated with the lowering of the hinterland, as opposed to the location of the source area, i.e. its proximity. The presence of laminated sandstones, and the gradational tops of the conglomerates, commonly associated with fairly fluidised flows, indicates that conditions were sub-aqueous.

Periodic erosion of the substrate is indicated by the presence of pale-green coloured fine-grained, micaceous mudstone clasts within flows. The mudstone at least must have been partially lithified to have been incorporated into the conglomerate and could not have travelled far from its original site of deposition. It is possibe that the mud clasts were derived from the underlying substratum during a phase of intense erosion, when the muddy sea floor was ripped up and the mud clasts were incorporated with the immediately succeeding debris flows.

3.2.2 Woodland Formation

Combining the exposures from the Haven (Figs. 3.3 and 3.4) and Woodland Point, the Woodland Formation can be subdivided into: (a) basal pebble conglomerate, (b) massive flags synonomous with Cocks and Toghills (1973) "bastard limestone" and Lapworths (1887) "Coralline limestone", and (c) shales interbedded with very fine-grained sandstones passing up into striped shales.

The basal conglomerate is observed at locality 206 (NS 178961), and is very distinct from the underlying Craigskelly Conglomerate. There is a very clear change in clast composition with the introduction of dolomite clasts to an assemblage of quartz, chert and relatively few igneous clasts together with a change in colour of the matrix from the Craigskelly olive-green to a medium light-grey. The Woodland Formation matrix-supported conglomerate is very poorly sorted with clasts ranging in size from 0.1 to 3.5cm, generally elongate to tabulate in shape. There is a noticeable reduction in grain size from the Craigskelly Conglomerate to the Woodland Formation and increase in matrix content. Calcium carbonate acts as a competent cementing agent. Within 20-30cm of the postulated base the conglomerate grades into medium light-grey coloured very fine-grained sandstone and siltstones. Dispersed throughout the sandstones and siltstones are abundant flasers and rare graptoloid fragments.

North of the Horse Rock there is a break in the section of 14m (Fig. 3.10), after which there is a very small exposure composed of grey coloured siltstones and very thin, i.e. 1cm thick mud layers weathering a darker yellowish-brown colour. Occurring at the bases of the siltstones were very small-scale slump structures of less than 3.0cm height (Plate 2.3.3). Stratigraphically above this are three small, less than a metre wide, rugged exposures which protrude from the sand of a small beach (localities 212, 213 and 214, NS 179962). At the base of locality 212 there are a number of small pebbles, generally of low sphericity and less than 17cm in diameter. Clast composition is dominated by quartz (Plate 2.3.1). The succeeding beds are medium-grey to light brownish-grey coloured crystalline limestones weathering yellowish-brown, and light whitish-grey

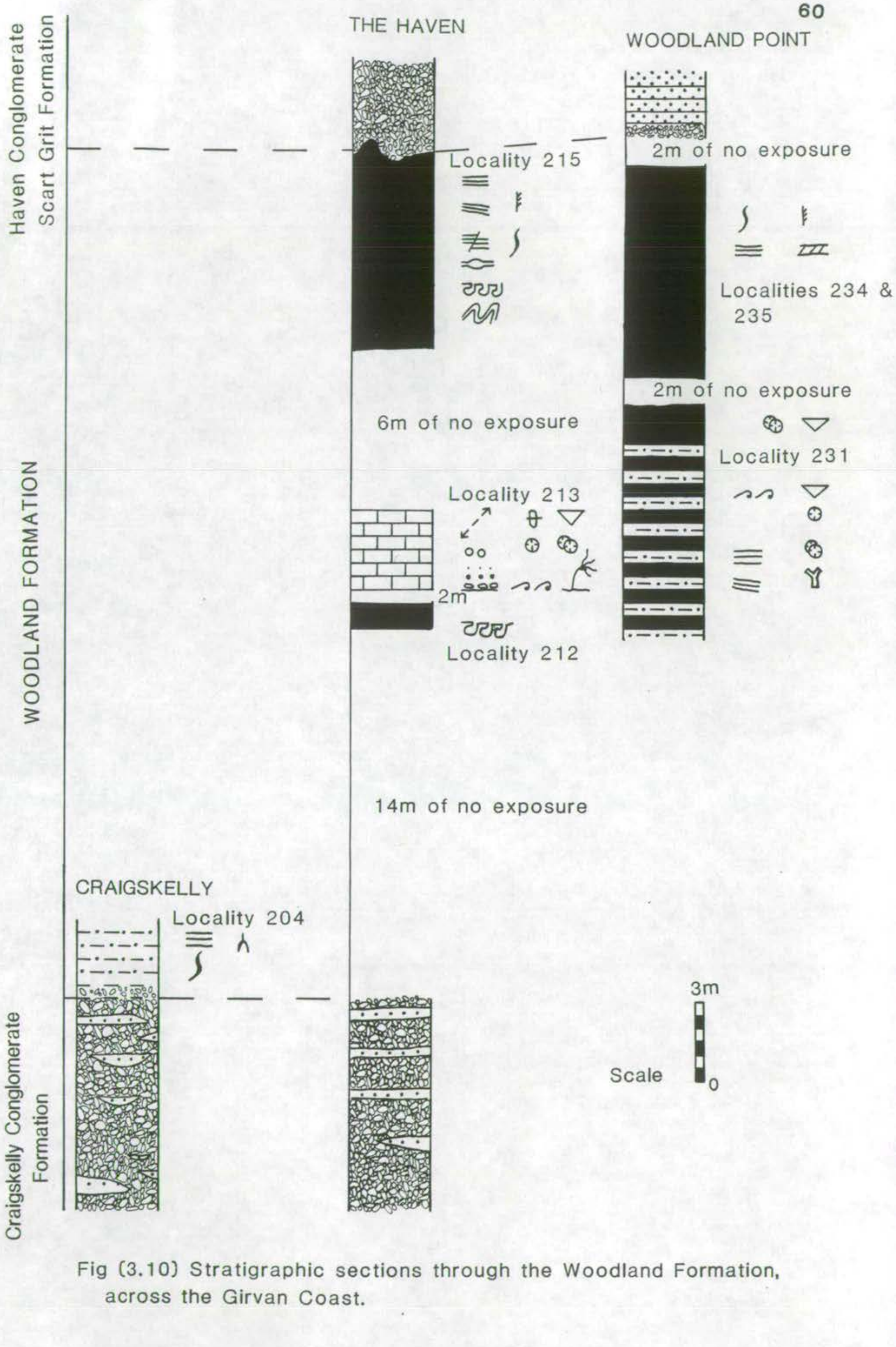


Fig (3.10) Stratigraphic sections through the Woodland Formation, across the Girvan Coast.

coloured medium-grained sandstones. The rocks have weathered in a nodular fashion. The more resistant bands being crystalline carbonate lenses. Freshly cut slabs reveal the presence of very thin laminations, which at first appear to be stromatolites, and scattered thin interbeds of discontinuous dolomitised biomicrite.

The presence of stromatolites has not been previously documented in the Silurian of the Girvan region, neither in the Craighead Inlier nor at the coastal section. Cryptalgal stromatolites are laminated structures composed of sand, silt and clay sized particles and micrite. Laminations are very thin, usually less than a millimetre in thickness, marking greater or lesser concentrations of carbonate and other debris and originate from a combination of several kinds of filamentous and coccoid green and blue-green algae binding the sediment together.

Whereas the sediment has been severely dolomitised, thus hindering the detailed study of the structures, any resemblance of the laminations to stromatolites is only superficial. The structures are few in number, randomly distributed and not consistent. Furthermore no associated filaments which might have been of algal origin were observed. The laminations are elongated and flattened approximately 1.2cm to 2.9cm in diameter, and appear stacked on top of each other with up to a maximum of six. Significantly, thickness of the laminae decreases from the middle outwards. Since there is an abundant brachiopod fauna composed of thick and very thin valves, it is more likely that these structures in fact represent stacked disarticulated brachiopod valves. Furthermore, in one particular instance, one set of stacked valves orientated convex up, is 'truncated' by another set of stacked valves orientated perpendicular to it. Some of the valves are pyritised, whilst the whole of the rock has been dolomitised.

The light-grey coloured, dolomitised biomicites are approximately 1-4cm thick, yielding an abundant but low-diversity fauna of disarticulated brachiopods and corals. Very small (over a millimetre in diameter) quartz grains of low sphericity produce a very poorly sorted texture. Under close inspection it is evident that the brachiopod valves are not randomly distributed. In places they occur stacked on top of each other, either convex or concave up and, as described previously, may even show imbrication. Crescent-shaped cavities occur where shells have been dissolved away. Three small elongate-shaped clasts, approximately 2.5cm in diameter, occurred underneath brachiopod valves - possibly compound corals which have been subjected to late stage dolomitisation. Within them a few small quartz grains (less than a millimetre) were present.

Overall there is a general swirled appearance, with very small patches of finer-grained material. This is attributed to the effects of bioturbation and individual burrows can be detected.

The dolomitised bands are up to 2cm thick, possessing a sharp almost-planar base and irregular top. Here the dolomite is coarsely crystalline, with crystals reaching up to 1 mm in diameter. A similar lens was found to be composed dominantly of disarticulated crinoid ossicles.

On the weathered surface very few concentrations of striations were observed. Individual striations were less than 1mm thick, whilst groups were up to 0.7cm wide and traced for a distance of up to 4cm.

An abundant but fairly low diversity fauna is comprised of fairly large compound corals measuring up to 6cm diameter and disarticulated brachiopods (Plate 2.3.2).

At Woodland Point, the lowest Woodland Formation exposures are characterised by very fine-grained calcareous-cemented sandstone interbedded with medium blue-grey coloured calcareous cemented mudstones (Fig. 3.10 and Plate 2.3.7). Accessible only at low water, the strata are exposed in patches projecting through the floor of the sandy beach, but on both sides of the peninsula they form more prominent ridges (locality 232). The sandstones are thinly bedded ranging from 0.12 to 0.53m thick, whilst the shales are much thinner, between 0.02 to 0.08m thick. Disarticulated brachiopods occur in abundance and rarely compound corals, confined to the mudstone horizons. Fossil concentrations can be as thick as 7cm, and may be traced up to a metre laterally. On ascending the sequence the sandstone to shale ratio gradually decreases such that the shales are dominant.

The top of the formation as seen at locality 216, (NS 179962), is characterised by faintly cross-laminated siltstones, intercalated with shales. Laminations are defined by colour changes - alternating light-grey to medium dark-grey weathering dusky-yellow, but towards the top the banded shales change colour alternating light-olive to moderate-olive. The laminations are also defined by subtle grain-size differences accentuated by the siltstones weathering into re-entrants of less than 0.5cm thick. Many of the laminations have been displaced by sets of parallel-orientated micro-faults, involving a displacement of no more than 5cm (Plate 2.3.4). Siltstones display boudinages measuring approximately 4-5cm long by 1.5cm high (Plate 2.3.5 and 6). The boudinages thin the siltstones, giving more positively skewed thickness distributions in the slumps than in the undeformed beds. The small slump folds tend to be less than 3cm high, having rounded upper limbs and tight angular lower limbs. In addition there are a number of sand dykes and sand pillars. Contrasting with these sediments the shales at Woodland Point do not appear to show syn-sedimentary deformation.

A dolerite dyke, approx 0.56m thick, trending northeast-southwest is intruded into the shales (locality 215). This weathers to a buff colour yet internally it is light-grey coloured and fairly finely crystalline. As the dyke is more resistant, it projects above the adjacent sediment. Immediately flanking the dyke, the shales are disturbed, mainly folded.

Just below the junction between the Woodland Formation and Haven conglomerate, at the Haven, the laminated shales are very tightly folded into disharmonic folds (Locality 221) (Plates 2.3.8 and 9).

Interpretation

Continuous sedimentation is reflected by the conformable and gradational transition from the underlying Craigskelly Conglomerate to the calcareous-rich pebbly conglomerate. The introduction of dolomite clasts and the abundance of calcareous-cemented siltstones heralds a change in the source rocks. Over a distance of approximately 0.20-0.30m the pebbly conglomerates fine upwards into very fine-grained calcareous cemented sandstones, indicating that the source area may have been eroded to such a low level that it could only provide fine-grained debris.

The small mounds occurring at localities 212, 213 and 214 are here interpreted environmentally, though with extreme caution. The lithologies consist of fine-grained calcareous-cemented sandstones, with pebbly sandstones at the base, and crystalline limestone horizons, interbedded with very fine-grained sandstones containing brachiopods, compound corals, solitary corals and bryozoans.

Both the brachiopods and crinoids are disarticulated, and the fauna is evidently transported. The brachiopod valves appear to be stacked, with as many as 5 to 6 piled on top of each other and may be either convex-up or convex-down. If these had been deposited by turbidity currents it is more likely that they would have displayed a more random distribution. What seems more probable is that the brachiopod shells have been sorted by a strong current envisaged as washing over a hard substratum, and flipping the valves over on to their stable position, so that they became stacked and occasionally imbricated. Such sorting most probably occurred during storms, on sediment below the fair-weather wave-base, sufficiently shallow enough to be disturbed by these sporadic storm events.

Breaks in sedimentation are recorded by the presence of bioturbation indicative of a burrowing fauna which may have re-established itself shortly after the sediment was deposited. Conditions at the substratum-water interface must have been aerobic.

Two alternative interpretations can be put forward to account for the occurrence of the lithologies exposed on the three mounds. The first involves a minor regression near a topographic rise on the sea floor, creating shallow conditions suitable for the development of carbonate-rich facies. An example of such a setting is that described by Ruiz-Ortiz (1983) from the middle member of the Loma del Toril formation (Kimmeridigian-Lower Tithonian) in the Betic Cordillera, Southern Spain. This is composed firstly of unit 'A' conglomerates (the lowest beds) with carbonate clasts and matrix, 0.40-4m thick, pinching out laterally and giving way to pelagic limestones. Secondly there are unit 'B' conglomerate beds intercalated with turbidite calcarenites displaying thinning and fining-upward cycles and calcarenites possessing typical turbidite features (erosive bases, good development of textural grading and vertical sequences of internal structures). And finally there are unit 'C', thickening and coarsening upward calcarenite sequences. These are interpreted as making up a regressive suite beginning with lower-slope valley conglomerates, channelised fining-upward calcarenites of depositional-lobes, thickening-upward calcarenites of depositional lobes, basin plain marls, and finally marly limestones with few turbidite beds. The estimated thickness of this re-sedimented carbonate material is given as 250m (Ruiz-Ortiz, 1983) which contrasts markedly with 6m of the Woodland Formation.

The second hypothesis advocates that a carbonate facies developed in shallow sub-tidal conditions at the top of the slope. A major event such as fault movement, an earthquake or overloading of sediment may have triggered downslope movement of large blocks of material. The semi-consolidated sediment mass would have retained some internal coherence (bedding) and moved along a basal plane of failure. Seismic profiling has shown that slumping can occur on gentle slopes as well as in the deep sea (Lewis, 1971; Roberts, 1972).

Crucial evidence includes:-

1) The change in the composition of the source area, yielding abundant dolomites and calcareous-cemented siltstones, requiring the existence of a carbonate facies which would provide the debris.
2) The juxtaposition of these calcareous sediments with the overlying laminated mudstone over the short distance of 2-4m. The laminated mudstones display Tc-Td Bouma sequences, associated with distal turbidites but there is no evidence of the more proximal lithologies. A local hiatus may account for this discrepancy.
3) The occurrence of a shallow marine fauna within the carbonate sequence composed of brachiopods, compound corals and bryozoans. This overlies siltstones containing graptolite fragments at locality 206, and underlies shales containing graptolites at locality 216. Such a juxtaposition implies that the sediments were deposited in differing environments.
4) The occurrence of synsedimentary/tectonic deformation within the top of the Woodland Formation at the Haven, including slumps, microfaults, boudinages and tight folding. Specificially the folding is seen only at the Haven, whereas there is little evidence of folding in the mudstones at

Woodland Point. Furthermore neither the underlying Craigskelly Conglomerate nor the overlying Scart Grits have been affected by folding.

5) Unstable environmental conditions reflected by periods of erosion, when the underlying sea floor was being eroded, resulting in the inclusion of mud clasts in the underlying Craigkselly Conglomerates and incorporation of bioclastic siltstones and shale clasts from the Woodland Formation into the overlying Haven Conglomerate Member.

6) The apparent discordance of the strike of bedding in the three mounds, compared to the general strike of the rest of the sediments.

7) The presence of very fine parallel striations with small steps orientated normal to the striations and smooth surfaces exposed on the mounds which resemble slickensides commonly associated with fault movement.

8) And finally, the topographic relationship of the three mounds, which resemble small transported blocks.

All these factors taken together favour the second alternative that the three mounds at localities 213, 214, 215 are allochthonous, having slid down to their present position. Admittedly, however, discordance of the strike of bedding and the parallel straitions could be associated with late tectonic features. Resedimentation of shallow water and slope facies carbonates by debris flows into deeper water is well known (e.g. Cook & Taylor, 1977; Davies, 1977; McIlreath, 1977). The term olistostrome was erected by Flores (1956, 1959) to describe 'a sedimentary body of lithologically or petrographically heterogeneous material consisting of two parts intimately admixed: a finer-grained matrix which supports bodies of more coherent material (clasts or olistoliths)'. It shows no well defined stratification. The term however has been used in different ways and has become synonomous with orogenic landslides, disrupted nappes, slumps, turbidites and normal sediments containing exotic blocks (e.g. Beneo, 1956; Facca, 1956; Badoux, 1967; Görler & Reutter, 1968; Elter & Trevisan, 1973).

At the Haven, the overlying fine-grained siltstone-shale couplets representing Tc-Td Bouma sequences show evidence of slumping in the form of small- and large-scale folds. Since these folds occur in otherwise undeformed sedimentary rocks they are distinguished from the products of tectonic deformation. Further evidence indicative of soft-sediment deformation at or near the sediment-water interface includes the following points:

1) Occasionally the folds show fluidisation, liquefaction, flame structures and dewatering features in their cores, as well as in the rest of the sediment.

2) The small-scale folds in individual siltstone beds lack a geometrically-related mineral veining.

3) Typically the folds have rounded upper limbs and tight angular lower limbs suggesting that the lower limbs have collapsed under the weight of the overlying limbs.

4) The close spatial association of the slump folds and boudins implies that the boudins also originate from the slumping. The boundinages arise from tensional forces, developing by the stretching of competent beds, namely the siltstones, producing pull-apart structures and necks. From either side the necks become infilled with the incompetent material, the shale, and eventually the neck breaks.

5) The erosional contact between deformed sediments and normal strata (the junction between the top of the Woodland Formation and the Haven Conglomerate) may also be diagnostic of slumping (Woodcock, 1979).

Many of these observations comply with those made by Naylor (1981). Such slump structures may have formed by the sliding of a superficial layer down an inclined surface so that it piled up as a folded body at the foot of the slope. The beds suffered slumping and sliding, becoming disrupted by folding and boudinage and, when slumping was over, later turbidites built out over the olistostromes. As a result, the olistromes became overlain by slumped siltstone-shale couplets.

In general, slumping is caused by high sedimentary rates leading to: 1) build-up of high pore fluid pressures, 2) erosional oversteepening of slopes, or 3) seismic triggering (Morgenstern, 1967; Ryan & von Rad, 1977). There appears to be no real evidence of increasing pore-fluid pressure, nor erosional steepening of the slope, whereas there is evidence of dewatering in the shales, a marked unconformity at the base of the Haven Conglomerate heralding influx of coarse debris. Thus the slumping may have been triggered by seismic activity.

A number of separate criteria indicate that the very fine-grained sandstones and mudstone couplets at Woodland Point (locality 232) are typical turbidites. The beds are laterally continuous and of regular thickness, can be traced for several metres and are composed of alternating coarse- and fine-grained beds; all of which compare easily with the classical Bouma model (1962). The faintly cross-bedded sandstones are typical of unit Tc whereas the mudstones are equivalent to Td Bouma sequence, and are the products of turbidity currents deficient in coarse sediment, perhaps the fine-grained tail of a larger denser current. The sediments accumulated in an environment remote from the site of coarse clastic deposition (Walker, 1967), referred to as thin-bedded turbidites after Mutti (1977). At Woodland Point the sequence fines upwards into siltstone-mudstone couplets, Td-Te Bouma sequences. Much finer-grained muds were deposited by suspension sedimentation, and the silty laminae are the products of small-scale turbidity currents or bottom currents.

This thinning, fining-upward sequence traced from the Craigskelly Conglomerates, through the Tc-Td turbidites into Td-e turbidites of the Woodland Formation represents the progressive abandonment of the channel and the deposition of progressively thinner and finer beds from smaller flows in the channel.

3.2.3 Scart Grits Formation

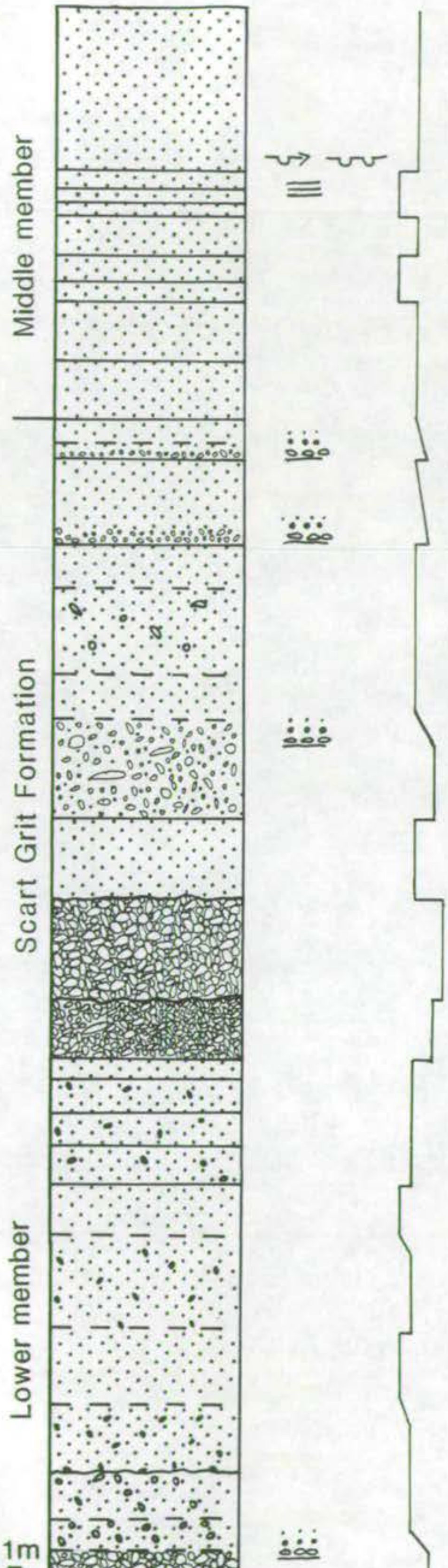
Haven Conglomerate

The base of the Scart Grits is marked by a conglomerate referred to by Cocks and Toghill (1973) as the Quartz Conglomerate. Though this name might suggest otherwise the conglomerate is not monomictic since igneous clasts and large ripped up mudstone and bioclastic siltstones originating from the underlying Woodland Formation are very important constituents. Therefore, it is proposed to call the conglomerate the Haven Conglomerate, giving it the status of the basal member of the Scart Grits.

At locality 215 (NS 179962), the base of the conglomerate lies unconformably on the Woodland Formation (Plate 2.4.1 and 2). Anomalously large clasts up to 28cm in length occur near the base of the conglomerate (Plate 2.4.3 and 4) and were derived from the underlying Woodland Formation. In general the clasts are of low sphericity, rod-, blade- and tabulate-shaped and are fairly angular. The conglomerate is moderately sorted with pebbles varying in size from 0.2 to 5cm, with a few clasts as large as 11cm, (Plate 2.4.5) occurring in a light bluish-grey coloured matrix. Although ungraded there are a few pale-red coloured coarse-grained sandstone beds, possessing irregular bases and sharp tops. Unit thickness does not exceed 0.70m. These sandstones appear to be internally structureless and also unfossiliferous. There is a gradual upward reduction in clast size (Plate 2.4.6) eventually fining upwards into the coarse to medium-grained sandstone of the Scart Grits (Plate 2.4.7 and 8).

Scart Grits

The most complete exposure of the Scart Grits occurs at Woodland Point headland, locality 226 (NS 169953), where it forms a long reef, resembling a slightly raised platform (approx. 240m by 40-50m) (Plate 2.5.1). At high water it forms a rugged island, while at low tide it is united to the main shore by a low and partly sand covered beach occupied by patches of Woodland Formation and much older Barren Flagstone (Ordovician) (Fig. 3.4). Since the top of the Formation is submerged during low tide, the minimum thickness is thought to be 28m thick. Here the base of the Scart Grits is represented by poorly-sorted pebbly sandstones grading upwards into coarse- to medium-grained pale-red coloured sandstones (Plate 2.5.2). Within the pebbly sandstones the clasts are generally less than 15cm diameter and more commonly between 0.7-8.0cm, composed of low sphericity, angular clasts of quartz, dolomite and igneous clasts. One



Thickly bedded,coarse grained sandstone.Sole of bed displays large flute and load structures.

Medium and thickly bedded,coarse grained sandstones.

Small scale fining upwards sequence:pebbly,poorly sorted sandstone fines up into a medium grained sandstone.Faintly laminated at the top of the unit.

Matrix supported,pebbly conglomerate.Clast composition includes:quartz,jasper,a few igneous,metamorphic rock fragments,crinoidal limestone,generally less than 4cm in diameter. Dolomite clasts are up to 19cm.

Poorly sorted,clast supported pebble conglomerate, ,generally less than 1.5cm.Infrequently reaching a max. of 12cm diameter.

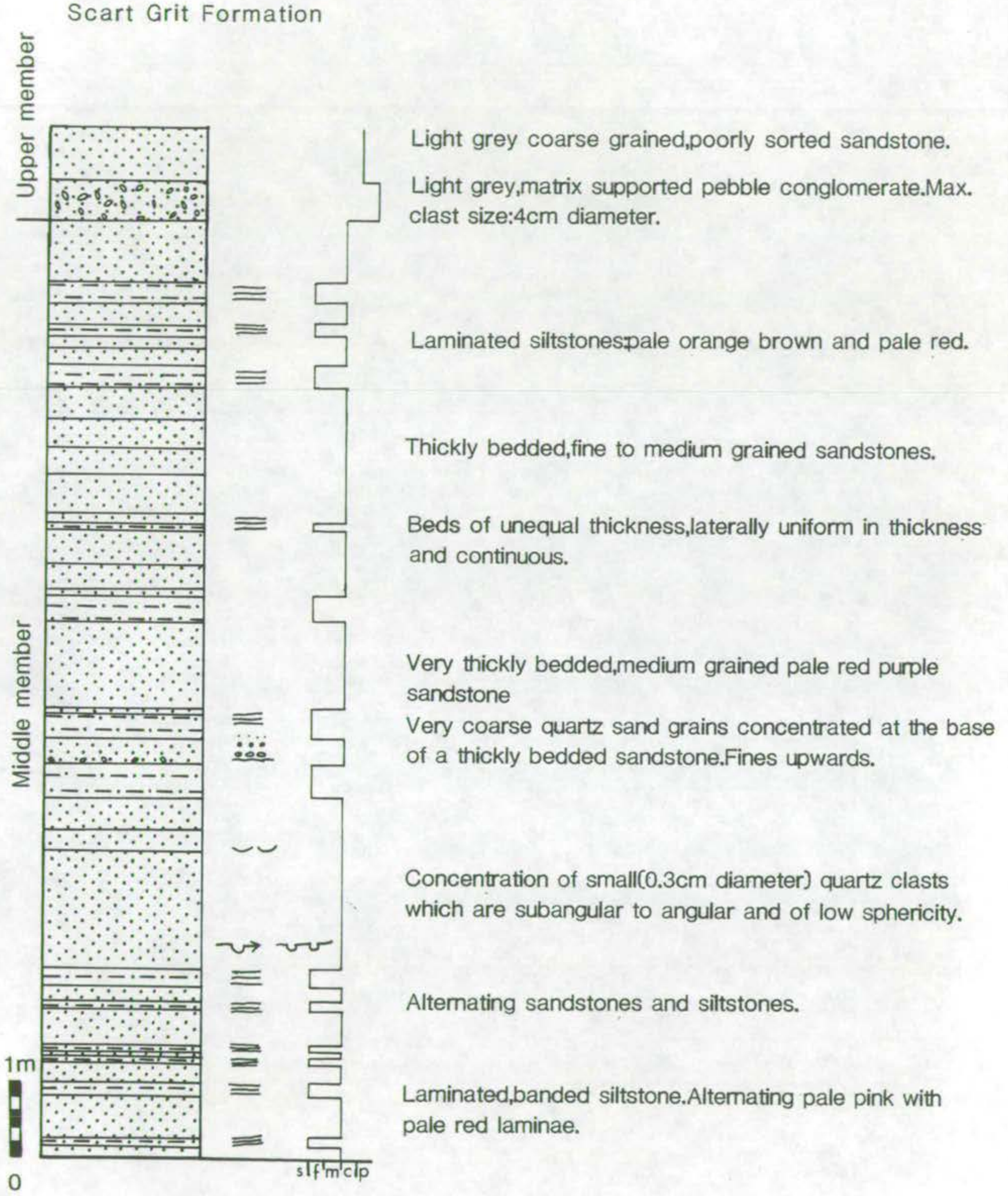
Moderately sorted pebbly sandstones.Max. clast size:0.8cm.

Thickly bedded,coarse grained pale red purple sandstones, granule to pebble sized clasts of quartz and jasper.

Clast supported,poorly sorted pebble conglomerate.Max. clast size 6cm composed of quartz,jasper,dolomite and lava clasts.

Fig(3.11) Stratigraphic section of the Scart Grit Formation.

Locality 225



Fig(3.12) Continuation of stratigraphic section of the Scart Grit Formation (locality 225).

unusual rounded clast (approx. 5-8cm diameter) was composed of white crinoidal limestone. No preferred orientation of the clasts is evident. Generally the bed thickness varies from 0.11 to 0.44m for both the pebbly sandstones and sandstones (Fig. 3.11 and 3.12). The sandstones are coarse-grained with a mean grain-size of 0.1cm, but small-scale fining-upwards sequences occur regularly, whereby the coarser base of the unit with a mean grain-size of 0.5cm grades up into a medium-grained sandstone (0.4mm). Eventually pebbly sandstone dies out and the rest of the formation comprises of very thickly bedded (ranging from 0.30 to 2.28m thick) medium-grained, poorly-sorted pale red-purple coloured sandstones interbedded with pale orange-brown and pale-red coloured rippled siltstones (Plate 2.5.3). Markedly thinner, the siltstone units range from 0.07 to 0.45m in thickness. On the soles of many of the sandstone beds slump structures, load casts, ball structures and wide flute structures are present. The flutes are fairly bulbous with rounded noses ranging in size from 3cm to 7cm. Load casts are irregularly shaped, generally rounded (Plate 2.5.4). Noticeably there are no groove marks present. In addition between the sandstone and shale there are concave upward dish structures (Plate 2.5.5 and 6). Also dish structures are present near the base of the sandstone where there are a few faint dish structures typified by thin, i.e. less than a mm, dark lines representing slightly more clay-rich zones. These form a pattern of successive concave up dish structures, no greater than 7.0cm (Plate 2.4.8).

Near the top of the exposure, locality 227 (NS 169954), there is an anomalous pebble horizon (Fig. 3.12). The pebbly sandstone is thickly bedded, approximately 0.55m thick, and contains low- to moderate-sphericity clasts composed of dolomite, quartz and chert which are less than 10cm in diameter (ranging from 0.5 to 8cm). The associated matrix displays a light-grey colour and has a matrix-supported texture.

Interpretation

A significant time lapse is represented by the unconformity at the base of the Haven Conglomerate Member. At locality 215 the incorporation of large siltstones and shale clasts, obviously derived from the underlying Woodland Formation, indicate that the shales must have been at least partially lithified prior to inclusion. Furthermore, near the contact the shales are tightly folded whereas the overlying conglomerates are not. Therefore it is concluded that after depositon of the shales there was a period of syn-sedimentary deformation accounting for the micro-faulting. The lithified sub-stratum was eroded and the shales were ripped up and were later incorporated into the conglomerate.

The unconformable base of the Haven Conglomerate, the clast-supported texture, the lack of obvious bedding and lack of internal structure implies that the conglomerates were rapidly deposited and are the products of a debris flow. Since the flow was incompetent the sediments were unable to form distinct beds.

The marked increase in grain-size from shale to pebble conglomerate suggests rejuvenation of the hinterland permitting the influx of coarse detrital material associated with a new channel incising the fan.

The overlying sandstones (constituting the Scart Grits) were deposited by a similar process, viz debris flows, but the sediments were slightly more fluidised. The pebbly sandstones, grading into coarse-medium grained sandstones in the lower sections of the Scart Grits, were deposited by sandy high-density turbidity currents. Lowe (1982) recognises three main stages namely, 1) a traction sedimentation stage, 2) a traction carpet stage, and 3) a suspension-sedimentation stage, reflecting increasing flow unsteadiness and collapse of the high-density suspension sediment cloud. The sequence as seen at locality 226 conforms closely to this ideal and shows a basal sandy bed and overlying inversely-graded unit (the traction carpet deposits), and finally a sandy top layer, deposited by suspension which may be graded and/or contain water escape structures.

Evidently, after initiation of the sandy high-density turbidity current some of the load was deposited, forming a sand bed. Because the current may have been locally erosive some of the bases of the sandstones show some scour (Walker, 1978). With the increase in flow instability the suspended sediment load became progressively concentrated toward the bed, and consequently transport in the bed-load layer became increasingly dominated by grain collisions (Bagnold, 1956; Shook & Daniel, 1965; Shook et al. 1968) resulting in the formation of a basal particle layer. This layer was maintained by dispersive pressure and the settling of coarse-grained particles from above. Hiscott & Middleton (1979) have recognised the occurrence of successions of inversely-graded coarse-grained sand to granule layers in the lower parts of some proximal turbidites. They suggest that when forced by continued sediment fall-out from the overlying flow such traction carpets will collapse and freeze. Subsequently, new carpets reform at the rising bed surface. This is also illustrated at locality 225. Furthermore the variation in the thickness of the inversely-graded unit, at locality 225, complies with the observations of Bagnold (1954) and Lowe (1976) who recognise that thickness of the traction carpet, like that of true grain flows, is directly proportional to particle diameter.

The presence of dish structures and ball structures in the upper parts of the sandstone are the products of fluidisation. When the suspended load fall-out rates increased there was not enough time for a bed-load layer or an organised traction carpet to form. Thus deposition was directly by suspension sedimentation (Walker, 1978). Deposits formed by the direct sedimentation of dense suspensions are among the most loosely packed of natural sediments (Kolbuszewski, 1950; Allen, 1972) and, if cohesionless, such deposits can be described in terms of liquefied beds (Wallis, 1969) and are highly susceptible to post-depositional disturbance, particularly liquefaction (Lowe and LoPiccolo, 1974; Lowe, 1975). Liquefaction in the Scart Grits is clearly shown by the presence of dish structures.

Dish structures have been described by Stauffer (1967). They originate when laminations produced during mass-flow are modified and disrupted. The reason for the increase in concavity upwards of the dish structure is because of the larger volumes of fluid flushed through the higher parts of the beds (Lowe, 1975).

The rest of the Formation consists of typical Ta-Tb-Tc Bouma sequences. Although the beds appear to be very thickly-bedded, some beds reaching up to 2.5m thick, these are not amalgamated beds but in fact are the products of one very large flow. The formation of the load casts and flutes has already been discussed in the section on the Glenshalloch Shale (Chapter 2). The sole structures are noticeably larger than those found in the Td-Te sequences present in the Glenshalloch Shale. The flutes in the Scart Grits are not only wider and more bulbous, having a more rounded nose in plan view, but they are also coarser-grained. Furthermore tool marks and organic marks appear to be lacking in the Scart Grits. The massive nature of the thickly-bedded sandstone and the general scarcity of tool marks associated with these flutes indicates that flute filling was by suspension sedimentation and consequently there was no bed-load traction (Pett & Walker, 1971). If any tools were present it is thought that they were suspended above the bed in a highly concentrated mass of grains. The support mechanism was a combination of dispersive pressure and a high effective viscosity (Parkash, 1970). Flute scouring presumably took place at the nose of the current (Middleton, 1966) with suspension sedimentation occurring in the flutes and on the surrounding ball behind the nose.

Not only do the sandstones record continued sedimentation on the fan, but the gradual decrease in grain size, from conglomerate to medium-grained sandstones, is related to the gradual infilling of the channel. In terms of lateral distance the sediments were deposited further from the channel.

Therefore at the coast the Silurian sequence represents a series of overlapping lobes in which there were both lateral and down-flow transitions of conglomerates into sandstones and finer sediments.

Plates 2.1 - 2.4 (Chapter 3)

Plate 2.1

CRAIGSKELLY CONGLOMERATE FORMATION

Figures

1. Craigskelly (locality 204) composed of the Craigskelly conglomerates alternating with coarse-grained sandstones.

2. Close up of Craigskelly, showing eastern side at low tide. Very poorly-sorted, clast-supported pebble to cobble conglomerates are intercalated with a coarse-grained sandstone lens, which wedges out laterally. Scale: hammer 33 cm.

3. Craigskelly Conglomerate exposed at the Haven (locality 208). As the Craigskelly formation is more resistant to erosion it rises above the low-lying Ordovician exposures in the foreground.

4. Close up of the Haven showing the junction between the Ordovician in the foreground, and the Silurian (represented by the Craigskelly Conglomerate in the background). The Ordovician (the Shalloch Formation) is composed of medium-bedded, medium-grained sandstones alternating with shales.

5. Very poorly-sorted clast-supported conglomerate. Size ranges from grit to boulder sized clasts. The large boulder in the centre of view measuring approximately 50 cm in diameter is composed of granite. Generally the clasts are well-rounded but of low sphericity, elongate to tabulate shaped. Scale: hammer 33 cm.

6. Poorly-sorted pebble to cobble sized clasts in the Craigskelly Conglomerate at locality 204. The clast in the central field of view and the clast to the NNE of it are both composed of a reworked conglomerate. Scale: Pen 13.5 cm.

7. Poorly-sorted clast-supported conglomerate. Clast size ranges from pebbles to small cobbles. Many of the elongated clasts show a preferred orientation, almost appearing to be imbricated (locality 204). Scale: hammer 33 cm.

8. Eastern flank of Craigskelly (locality 204). Poorly-sorted, clast-supported pebble to cobble conglomerates interbedded with coarse-grained sandstones. The sandstones are not laterally continuous but wedge out laterally. Bed thickness varies laterally. Here the sandstone is displaced by a fault trending northwest-southeast. Scale: hammer 33 cm.

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Plate 2.2

CRAIGSKELLY CONGLOMERATE FORMATION

Figures

1. Medium-bedded, coarse-grained grey-olive coloured sandstone. Very low angle cross-stratification can be seen. This is overlain by a pebble conglomerate (locality 204).
   Scale: coin 2.8 cm.

2. Very large sandstone body up to 30 m thick at the widest point. However it thins dramatically to the north and eventually pinches out (locality 204). Scale: hammer 33 cm.

3. Reverse grading developed in the Craigskelly sequence at the Haven (locality 208). At the base of the unit the pebbly conglomerate is overlain by a conglomerate containing dominantly cobbles and pebbles. Thickness varies laterally. Gradually there is a decrease in grain size upwards, fining upwards into a medium-bedded coarse-grained sandstone.
   Scale: hammer 33 cm.

4. Close-up of photograph 3. The pebble conglomerate gradually fines upwards. At the base of the sandstone unit there is a concentration of small grit sized clasts composed almost exclusively of quartz. These fine upwards into a coarse-grained sandstone. Scale: coin 2.8 cm.

5. Coarse-grained sandstone interbedded between a poorly-sorted pebble and cobble conglomerate. Occurring within the sandstone is a discontinuous concentration of small pebbles generally less than 2 cm in diameter (locality 208).
   Scale: hammer 33 cm.

6. Very poorly-sorted conglomerate with pebble to cobble sized well-rounded clasts. The light coloured areas represent mud clasts which have been affected by compaction and consequently have lost their original shape (locality 208).
   Scale: coin 2.8 cm.

PLATE 2.2

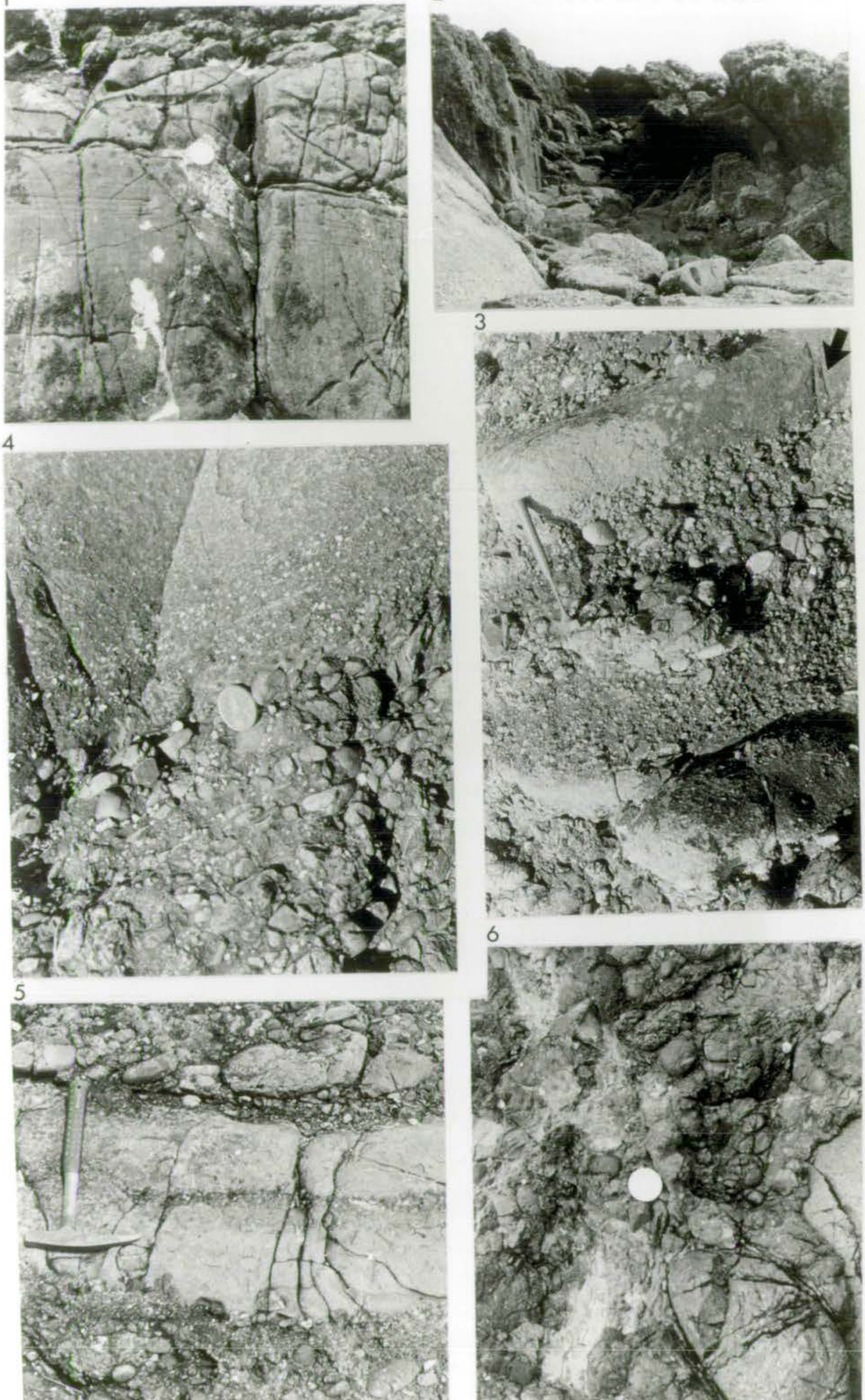

Plate 2.3

WOODLAND FORMATION

Figures

1. One of three low-lying rugged bosses, in the Haven (locality 212). Generally the dolomitised limestone has a nodular appearance. Scale: hammer 40 cm.

2. Close up of locality 212, showing disarticulated brachiopods, compound corals, including *Halysites*. Scale: coin 2.8 cm.

3. Small-scale slump structures occurring in a mudstone.

4. Fine-grained light grey coloured siltstones alternating with medium dark grey coloured shales in the Woodland Formation. The siltstones have been displaced by parallel orientated sets of micro-faults (locality 216). Scale: coin 2.8 cm.

5. Stage 1 of the formation of a boudin. The competent beds, namely the siltstones, stretch as a result of tensional forces, producing pull-apart structures and neck.

6. Stage 2 of the formation of a boudin. From either side the necks become infilled with the incompetent material, the shale, and eventually the neck breaks (locality 216). Scale: coin 2.8 cm.

7. Calcareous cemented fine-grained sandstones interbedded regularly with bioclastic shales. The sandstones are laterally continuous and of fairly constant thickness. Occasionally they possess low-angle cross-bedding (locality 203). Scale: hammer 33 cm.

8. Tightly folded Woodland Formation shales (locality 221). On the left there are exposures of Haven Conglomerate. Scale: hammer 40 cm.

9. Close up of the Woodland Formation, folded tightly into disharmonic folds (locality 221). Scale: hammer 40 cm.

PLATE 2.3

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Plate 2.4

HAVEN CONGLOMERATE

Figures

1. The contact between the underlying Woodland Formation and the Haven conglomerate at locality 215 is represented by an unconformity. Scale: hammer 40 cm.

2. Close up of the unconformity at the base of the Haven conglomerate. The actual contact is sharp and irregular (locality 215) Scale: hammer 40 cm.

3. Poorly-sorted pebble conglomerate in which clasts are dominantly composed of quartz. However there are very large mud clasts, measuring up to 28 cm, derived from the underlying Woodland Formation (locality 218). Scale: hammer 40 cm.

4. Close up of the previous photograph (at the point of the arrow), showing the laminated mudstone clast, displaced by a small fracture (locality 218). Scale: coin 2.8 cm.

5. Close up of the polymict, poorly-sorted conglomerate, containing pebble- to small cobble-sized clasts of quartz, siltstones and laminated shales (locality 223). Scale: coin 1.4 cm.

6. Moderately-sorted, pebble conglomerate, in which there are some large clasts of laminated siltstones derived from the Woodland Formation. The smaller clasts are almost exclusively composed of sub-angular to sub-rounded quartz. Clast sphericity is low to moderate (locality 218). Scale: coin 2.8 cm.

7. Coarse-grained pale red coloured sandstone bed, interbedded with the Haven Conglomerate. Beds tend to vary laterally in thickness and are laterally discontinuous. The sandstones are poorly sorted containing small pebble clasts, often showing reverse and normal grading (locality 218). Scale: hammer 40 cm.

SCART GRITS FORMATION

8. Coarse-grained, pale red coloured sandstone occurring at the base of the Scart Grits (locality 219). The very faint concave upwards trending laminae represent dish structures. Scale: hammer approximately 10 cm.

PLATE 2.4

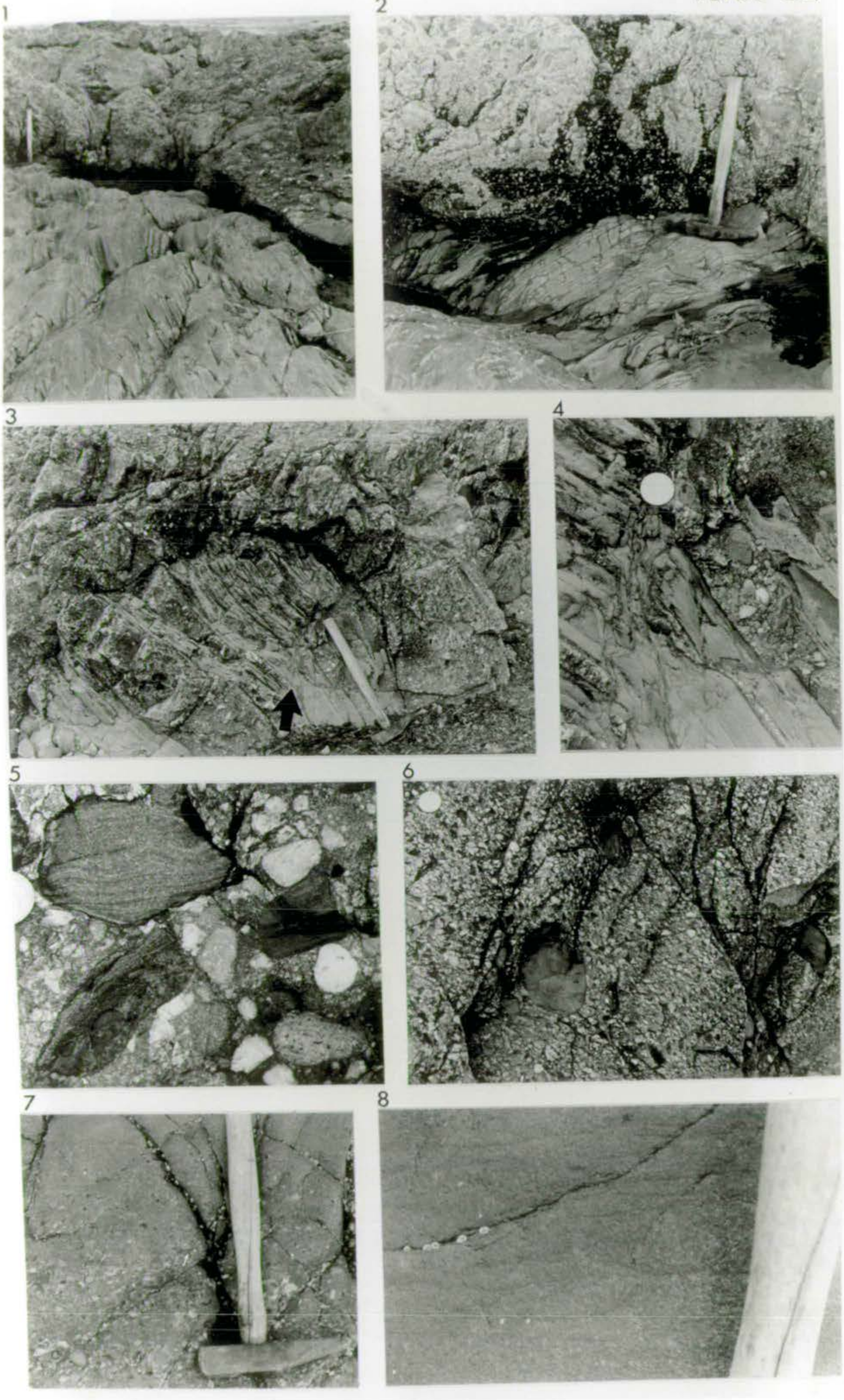


Plate 2.5

SCART GRITS FORMATION

Figures

1. Panoramic view of the main exposure of the Scart Grits at locality 225, Woodland Point, looking north. In the far background is Craigskelly and the Haven. The Scart Grits consist of very thickly bedded coarse-grained sandstones. Where the sandstones are interbedded with siltstones, the finer-grained beds have been weathered down.
   Scale: hammer 33 cm.

2. Very coarse-grained poorly-sorted sandstones intercalated with matrix-supported pebble conglomerates. Although polymictic, clast composition is dominated by quartz. Gradually the grain size decreases upwards (locality 225).
   Scale: hammer 33 cm.

3. Pale pink coloured siltstones interbedded with very thinly bedded fine-grained sandstones, and very thickly bedded, poorly-sorted coarse-grained sandstones (locality 225).
   Scale: coin 2.8 cm.

4. Sole structures on the exposed base of a very thickly bedded, very coarse-grained sandstone bed (locality 225).
   Scale: hammer 33 cm.

5. Possible fluid escape structures above the base of a very thickly bedded, coarse-grained sandstone (locality 225).
   Scale: coin 2.8 cm.

6. Possible fluid escape structures above the base of another very thickly bedded coarse-grained sandstone unit (locality 225). Scale: coin 2.8 cm.

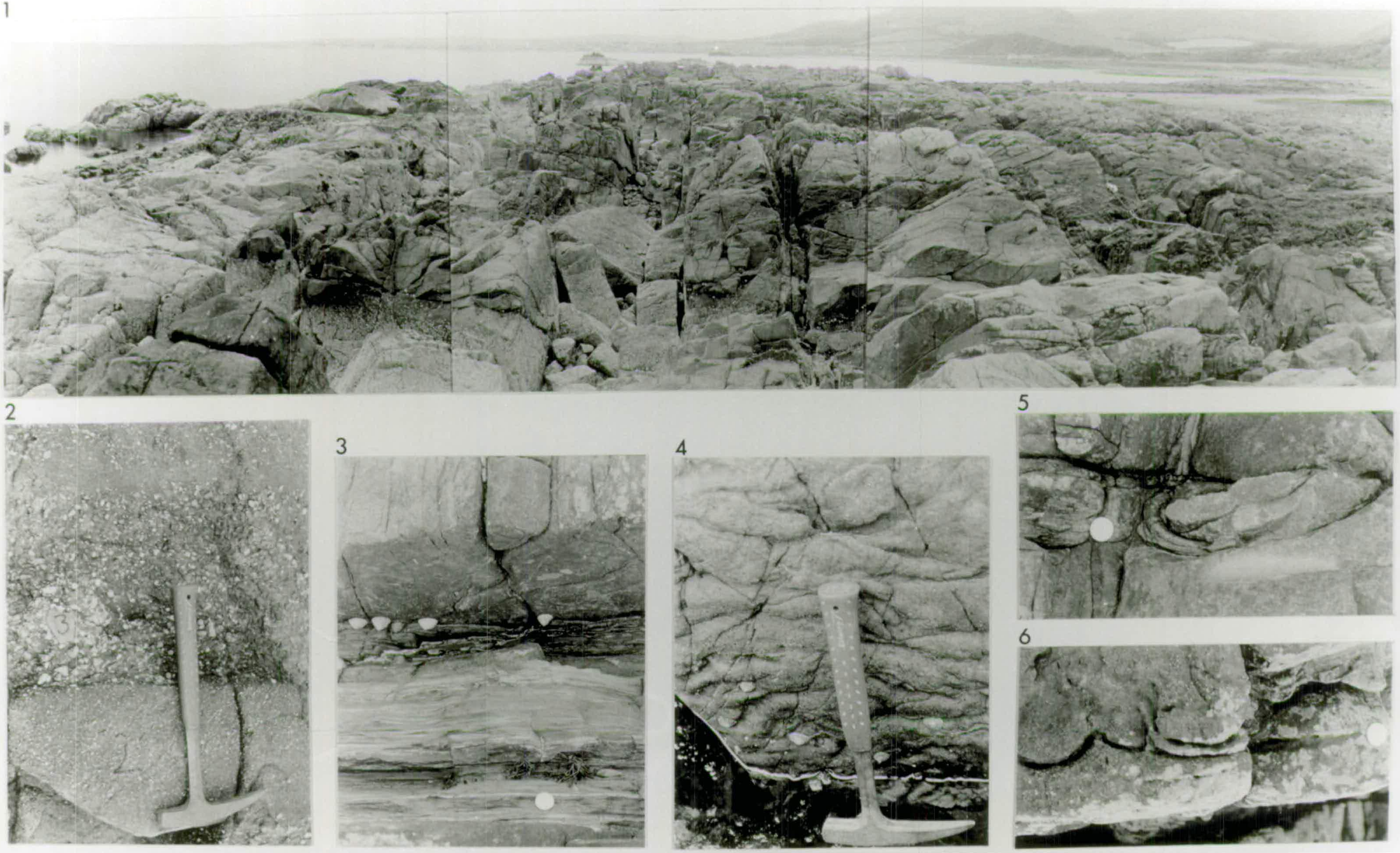


PLATE 2.5

CHAPTER 4

4. ANALYSIS OF THE CONGLOMERATES AT CRAIGHEAD AND THE COASTAL SECTIONS

4.1 INTRODUCTION

In recent years much literature has accumulated devoted to the analysis of conglomerate depositional environments. In particular, primary sedimentary structures such as bed thickness, grain size and angularity of grains have been used to determine different kinds of environmental setting. Whenever possible, such features were examined in the conglomerates of the Craighead Inlier (namely the Mulloch Hill, Newlands, Glenwells Conglomerates and the pebbly sandstone at the base of the Upper Saugh Hill Grits) and the coastal sections (the Craigskelly, Haven Conglomerates and the Scart Grits). In addition, the composition of the clasts and palaeocurrent data were taken into consideration, which both provides a basis for correlations between the two areas, and reveals the lithology and in general terms the location of the source.

4.1.1 Bed thickness

Bedding refers to rock units of general tabular form that display a definite lithological or structural unity. As with many structures bedding can be quantified. The regularity of a bedded sequence can be described in terms of uniformity in thickness from bed to bed, lateral continuity and uniform thickness within individual beds.

It has been observed in sandstones of turbidite sequences that grain size and thickness of a bed unit can be generally related (Feige, 1939; Potter & Scheidegger, 1966). Since bed thickness diminishes in a downcurrent direction (Scheidegger & Potter, 1971) proximal and distal facies can be distinguished.

Bed thickness may also be used in determining cyclicity (see reviews in Walker, 1970; Sestini, 1970). Ricci Lucchi (1969) demonstrated that vertical variations of bed thickness in a continuous turbidite sequence were not random, recognising recurrent groups of thicker beds which he called megarhythms after Ksiazkiewiz (1960) and in the following year, Mutti (1961) pointed out the existence of fining-upward cycles, in channel fills.

Factors influencing the cyclicity of major sand pulses in turbidite basins include variations of subsidence, rhythmic tectonic movements, variations of rates of erosion in source areas, multiple provenance of flows and variations of bottom topography (Ricci Lucchi, 1975). A different approach was proposed by Mutti & Ricci Lucchi (1972), Mutti & Ghibaudo (1972) and Mutti (1974) who concentrated on the internal organisation of cycles (mega sequences) which either thicken or thin upward. These can be compared with the coarsening-upward and fining-upward sequences of fluvio-deltaic environments. It was suggested that the cycles were related to the depositional environment and the various processes operating in it.

Vertical sequence analysis is valuable for:

a) establishing proximity to the source area,

b) differentiating between channelised and non-channelised portions in some ancient basins (Ricci-Lucchi, 1975) and

c) identifying cyclicity which reflects the dynamics of the most active part of a submarine fan, i.e. channelised from deposited lobes.

In ancient turbidite basins, the vertical organisation of both channelised and non-channelised sand bodies has been observed and then compared with that of fluvial-deltaic deposits (see Mutti & Ricci Lucchi, 1972; Mutti & Ghibaudo, 1972; Mutti, 1974). The filling of channels is characterised by thinning- and fining-upward mega-sequences, possessing a sharply defined, erosional base, whereas thickening- and coarsening-upward sequences reflect the accretion of depositional lobes.

4.1.2 Grain size

Despite the wealth of existing literature, it is questionable whether grain size distribution is truely representative of any particular agent and or environment.

It has been suggested that grain size distribution is related to:-

a) hydrodynamics - for example hydrodynamics can account for the biomodal distribution of many coarse-grained river sediments, whereby the coarser grains are the products of traction transportation and the finer grains are the products of saltation transport (Udden, 1914).

b) source materials - and their susceptibility to disintegration and breakage. This theory is advocated by Rosin and Rammler (1934), Tanner (1959), Kolmogorov (1941), and Smalley (1966).

Some workers including Udden (1914), Sindowski (1957), Friedman (1961, 1962), Moiola & Weiser (1968) have studied grading in sediments from various natural geomorphic environments, in order to see if there is relation between the two.

4.1.3 Shape

Shape is a product of a number of interacting factors (Sneed & Folk, 1958).

1) the original shape of the fragment before it enters the system, which is influenced by the degree of anistropy.

2) the environment in which the shape is modified - some geological agents have the capacity to modify the shape of a fragment in a different way. For instance

distinction between the redeposited products of rounding in beach of fluvial environments was made by McBride (1962) and Ricci Lucchi (1969).

Data can be obtained from direct measurement using Vernier callipers, measuring the three principal mutually perpendicular axes (after Dobkins & Folk, 1970), where a,b and c are length, breadth and thickness respectively. Using the ratios b/a and c/b, Zingg (1935) was able to discriminate shapes into four categories: oblate (bladed), prolate (rod), triaxial (tabulate) and equiaxial (equant). Unfortunately, difficulties arise with all the methods of measuring and expressing form or sphericity because such classifications are only qualitative descriptions and do not always bear any relations to the dynamic behaviour of the clasts during transportation, nor the composition of the clast. The problems of measurement have been examined and summarised by Griffiths (1967) and other co-workers. Barrett (1980) points out that even the best of the methods used for calculating shape have their limitations, since some measurements depend occasionally on subjective assessments such as location of the three axes and natural variables (e.g. rock type, particle size). Deductions made about ancient sediments on the basis of shape studies is therefore fairly subjective and should be used with some degree of caution. Measurements can only be easily made on unconsolidated material. Assessment of shape in consolidated sediment proves to be highly qualitative.

Since the clasts within the Mulloch Hill Conglomerate were easily extracted from the friable matrix, the Mulloch Hill Conglomerate is well suited for the study of clast shape. However the clasts from the Newlands Conglomerate (Craighead Inlier), the Craigskelly, Haven and Scart Grit Conglomerates (coastal sections) were almost impossible to remove, hence measurements had to be made in the field. Unfortunately poor exposures prevented measurements being taken for the clasts from the Glenwells Burn, Upper Saugh Hill Grit pebbly sandstones (Craighead) and from the Woodland Formation calcitic breccia and conglomerate, at the top of the Scart Grits (coastal section). In such cases, only qualitative observations could be made.

4.1.4 Roundness

Often roundness has been used synonomously with shape (Russel & Taylor, 1937), yet roundness in fact is independent of shape and actually describes the sharpness of the edges and corners of the clast. As with definitions of shape there are several methods used for establishing roundness. Wentworth (1919) defined roundness as r_1/R, where r_1=radius of the curvature of the sharpest edge and R= a half of the largest diameter. Krumbein (1940) preferred to study sectional or projected images of the particle clast, working with two dimensional figures. Subsequently he defined roundness as the average radius of curvature of the corners of the grain image, divided by the maximum circle.

For the purposes of this study, it was preferred, again to use the qualitative approach, utilising Pettijohns' (1975) and Powers' (1953) visual roundness charts combined with Pettijohns' descriptive definitions (1975), grading from angular to well rounded.

In environmental interpretations, the roundness of clasts are of limited use. Most rounding is acquired rapidly in the early stages of transportation, then rounding becomes slower the greater the distance travelled (Daubreé, 1879; Wentworth, 1919, 1922, 1922). Thus it is evident that angular to subangular gravels have not been moved far (Pettijohn, 1975). It has also been shown that there may be a limiting roundness, partly related to the lithology of the particle. Thus for example, the limiting roundness is lower in chert than in quartz or limestone (Sneed & Folk, 1958). Once acquired, it is very unlikely that the rounding will be lost. Caution must be made when examining quartz sands, because some grains and clasts may have inherited rounding from an earlier phase of transport, leading to misinterpretation.

4.1.5 Composition

The composition of a conglomerate is greatly determined by whether or not the source rocks form blocks when weathered and by their resistance to abrasive agents. Thus, the composition of a conglomerate does not always represent an accurate record of the type and abundance of the rocks in the source area. During transportation, the composition of the gravel may be modified so that unstable components, such as granite (which tends to disintegrate) are eliminated while, penecontemporaneously it becomes enriched in more stable components (such as quartzite, vein quartz) in a downstream direction. The disappearance of certain unstable rock types has long been noted. Hochenberger (in Grabau, 1913) not only recorded the downstream changes occurring in the River Mur but also estimated the distance of travel required to disintegrate and destroy various types of rock. Within a relatively short distance of transport gravels, unlike sands, can become compositionally mature; composed of only the most stable components.

Clearly the composition of the conglomerates may be used only as a general indicator of the lithology of the source area, and as a rough guide to the size of the gathering area. For a more accurate picture coarse- to medium-grained sandstones are more suitable for provenance studies.

Pebble counts, based upon point counts, were not made for the various conglomerates in the Craighead Inlier and the coast, because some rock types yield larger cobbles, and thus pebble counts would be biased. Instead, the range in composition of the clasts was determined by identification in the field and in the laboratory.

4.1.6 Cross bedding

Not only is cross bedding used as a criterion for determining the younging direction of a stratigraphic sequence (Shrock, 1948) but it can be used, combined with other directional structures, to ascertain palaeocurrent directions, paleoslope and sedimentary strike (Pettijohn, 1962; Potter & Pettijohn, 1963). This provides important data on the palaeogeography and additional information for facies interpretation. Measurements from different sedimentary units, as well as different lithofacies at a single exposure must be collected independently. The structures record either the direction of movement (azimuth) of the current or record the line of movement (the trend).

Suitable structures, for measurements, such as cross bedding and sole structures, were only found in the Mulloch Hill Conglomerate, at Craighead and in the Craigskelly Conglomerate, Scart Grits, at the coast. Consequently palaeocurrent indicators are very scarce.

4.2 MULLOCH HILL CONGLOMERATE FORMATION

4.2.1 Bed thickness

The conglomerate beds at locality 13 are laterally continuous but vary in thickness. Individual beds range in size from 0.30m to 1.50m thick, averaging 0.75m, although the maximum thickness is 1.80m (Fig. 4.1 and 4.2).

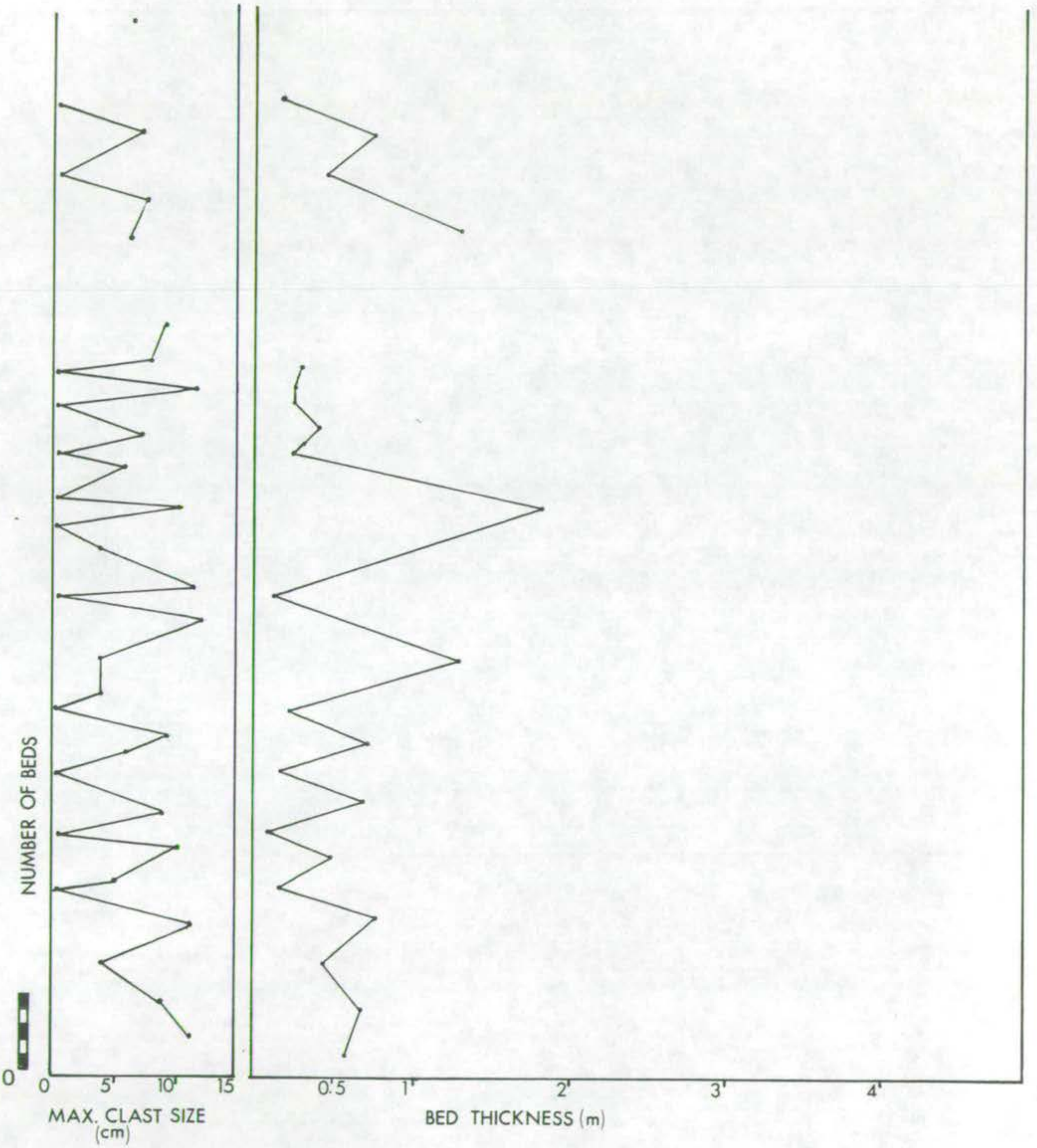
Notably the sandstone beds, which are regularly intercalated with the conglomerates, are much thinner, attaining a maximum thickness of only 0.40m, almost a third of the thickness of the thickest conglomerate bed. Bed thickness varies from 0.09 to 0.43m thick, with a mean of 0.20m thick and median (44%) sandstone bed thickness of between 0.20-0.29m thick (Fig. 4.3).

4.2.2 Grain size

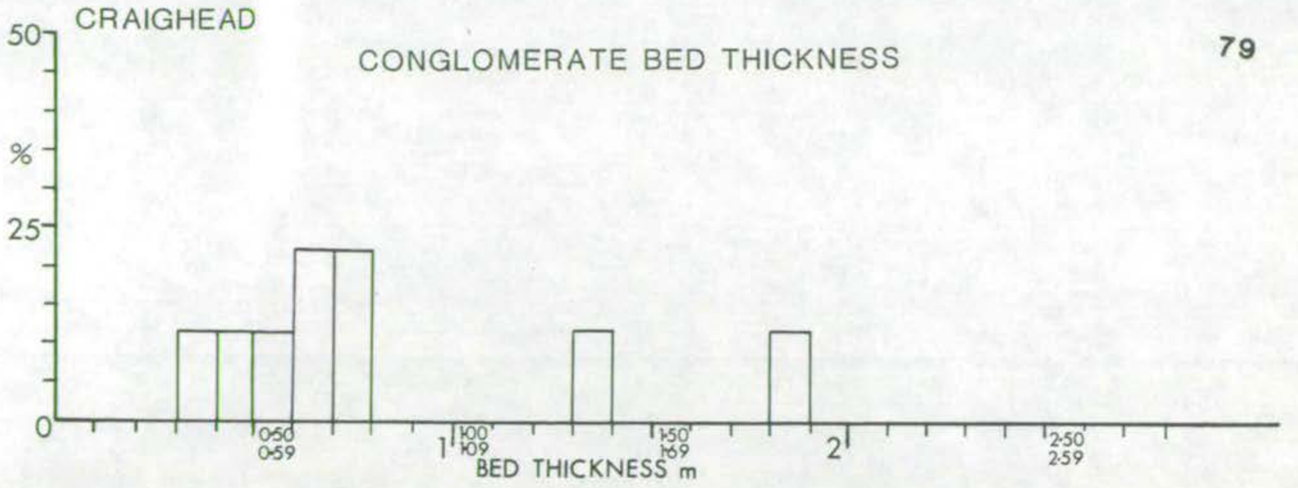
Maximum clast size in the conglomerate beds is 14cm (Fig. 4.1). Sorting is poorly developed, with clasts ranging from 1.0cm to 14cm in diameter. Within the logged sequence the maximum, average and range of the conglomerate clasts fluctuates, alternating from cobble to pebble conglomerates. These changes in grain size tend to be related to changes in bed thickness, for example Unit 14 is 1.80m thick, within which the maximum clast size is 12cm diameter; whereas Unit 2 is only 0.66m thick and the maximum clast size is 6.0cm diameter. Naturally there are exceptions to the rule, such as seen in Unit 12.

The sandstones are fine-grained to coarse-grained, often containing small floating pebbles up to 0.4cm in diameter. Clearly the decrease in grain size can be correlated

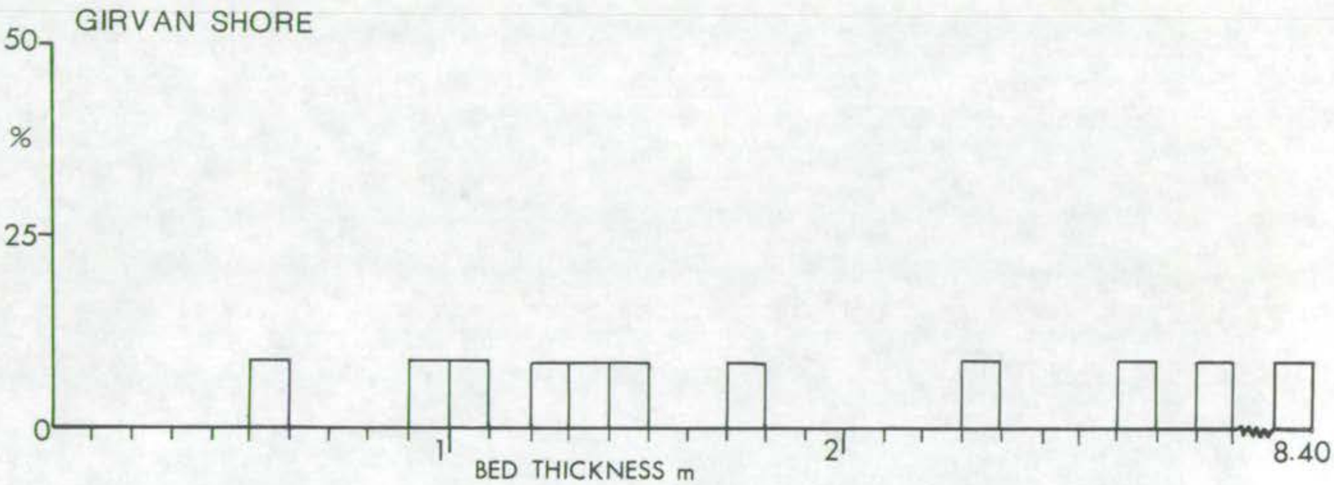
Mulloch Hill Conglomerate Formation (locality 13)



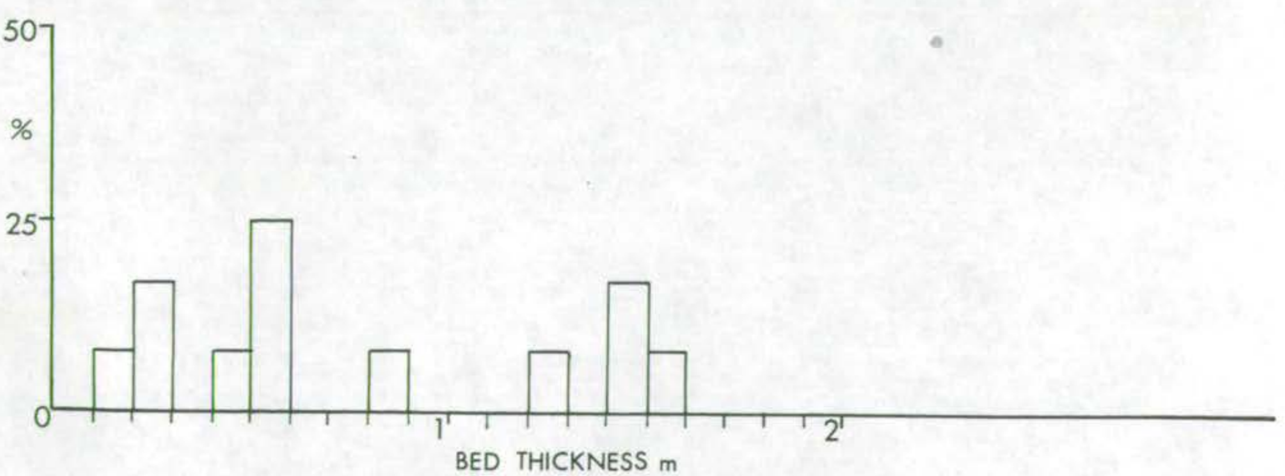
Fig(4.1) Vertical changes in bed thickness in the Mulloch Hill Conglomerate Formation,Craighead (locality 13,7 and 6).



Mulloch Hill Conglomerate Formation (locality 13)



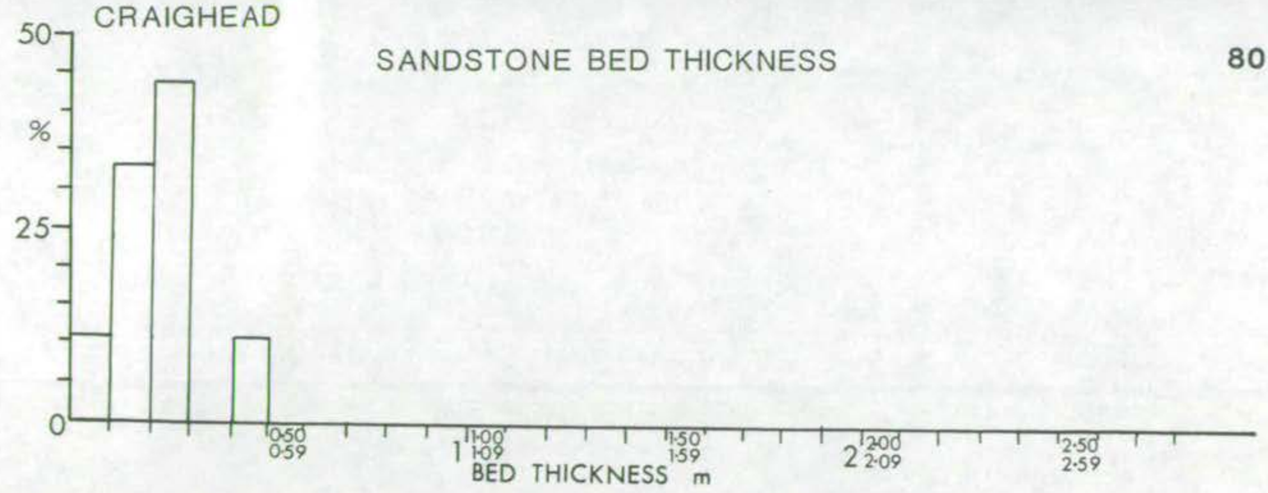
Craigskelly Conglomerate Formation (locality 204)



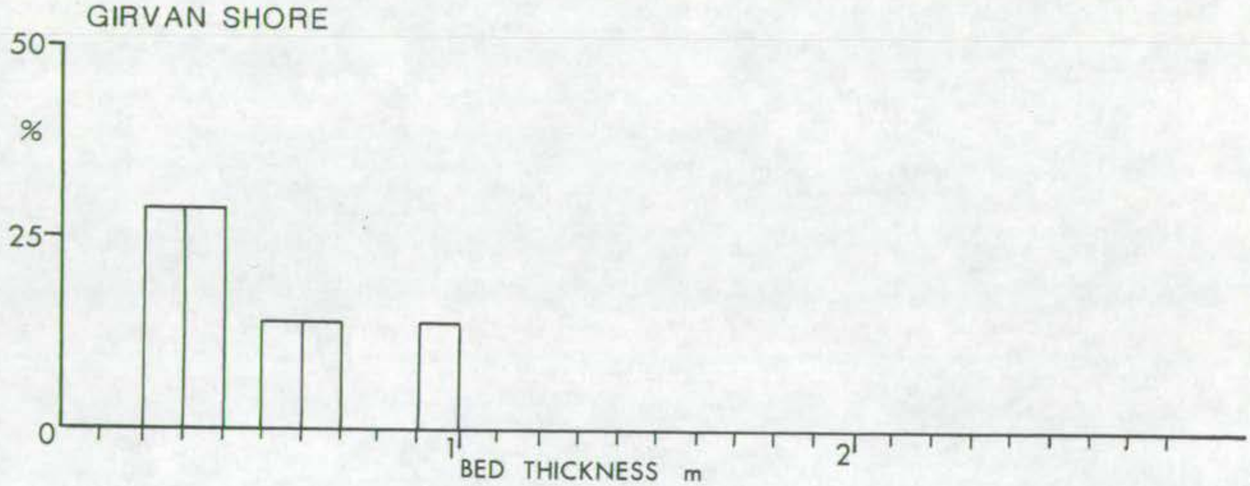
Scart Grit Formation (locality 225)

Fig(4.2) Histogram of the conglomerate bed thickness distribution in the Mulloch Hill Conglomerate Formation (Craighead),Craigskelly Conglomerate and Scart Grit Formations (Girvan Shore).

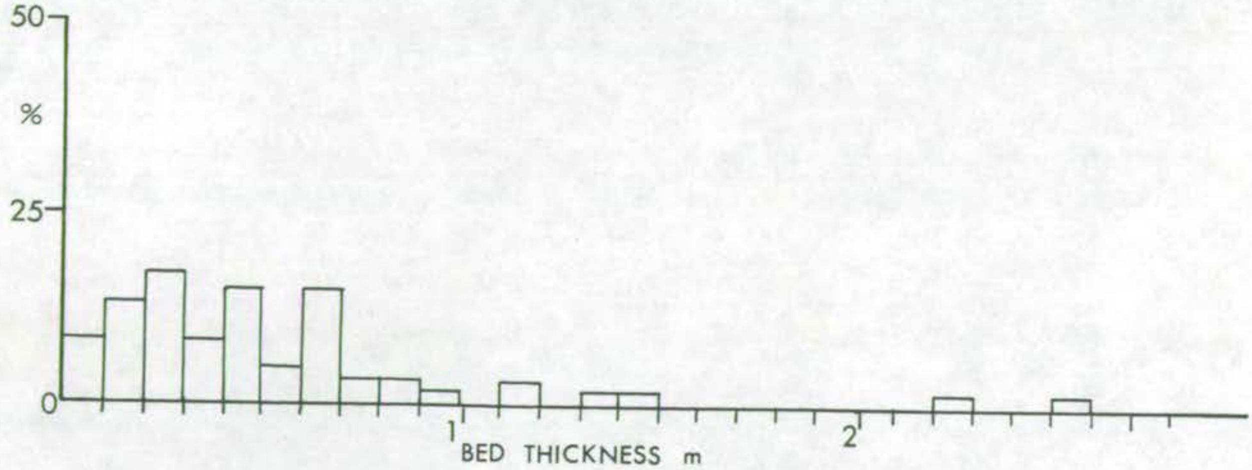
SANDSTONE BED THICKNESS



Mulloch Hill Conglomerate Formation (locality 13)



Craigskelly Conglomerate Formation (locality 204)



Scart Grit Formation (locality 225)

Fig(4.3) Histogram of sandstone bed thickness distribution,in the Mulloch Hill Conglomerate Formation (Craighead),Craigskelly Conglomerate and Scart Grit Formations (Girvan Shore).

with a decrease in bed thickness, suggesting that there is a relationship between bed thickness and maximum grain size. This supports Sadler's (1982) findings. Normally a turbidite is deposited when the turbulence flowing across a decreasing bottom slope decays with time. Decreasing slope combined with the loss of sediment reduces the shear velocity and so reduces the intensity of turbulence. Both the flow competence and capacity (the bulk of sediment carried) will decrease with time and therefore the amount of material deposited will be related to the maximum grain size deposits (Sadler, 1982).

The gradual reduction in clast size is not obvious at locality 13, where there is only slight reduction in maximum clast size from 14cm at the base to 8cm in diameter, near the top of the exposure. Better evidence is seen stratigraphically higher in the sequence, at locality 7, where maximum clast size is approximately 5 to 7cm in diameter.

4.2.3 Cyclicity

Despite fining upwards, the Mulloch Hill Conglomerate does not display a typically thinning-upwards sequence (Fig. 4.1). Superficially there is a gradual decrease in bed thickness from 0.40-0.70m to 0.20-0.40m. As the bed thickness of the conglomerates decrease, there is a corresponding slight increase in sandstone bed thickness from 0.9-0.15m to 0.22-0.27m at the top of the sequence. Furthermore it is apparent that the conglomerates display a number of minor cycles, which thicken and thin. Similarly the sandstone beds display minor thickening and thinning cycles.

Aggradation is well-known for producing fining-upward sequences in fluvial deltaic and tidal channels (Ricci-Lucchi, 1975) and can be assumed in the case of the Mulloch Hill Conglomerate. The Mulloch Hill Conglomerate probably represents the filling of a channel. Coarse-grained material would have been sporadically trapped in it when the channel was active. Deposition would have prevailed when the channel shifted flow, when a new channel was cut, or when the longitudinal gradient changed. As the section gradually shallowed and widened, and correspondingly the volume of flow decreased, the beds became much thinner. Eventually the channel became choked, as represented by the accumulation of the Glenwells Shale, and was abandoned. Care should be taken when interpreting sequences and bed thickness patterns as they do not always signify changes in the sub-environments, at the point of deposition. The general trend of the Mulloch Hill Conglomerate is one of an aggrading sequence and the minor fluctuations in bed thickness may be the result of changes in the point of supply, such as variations in the amount or type of sediment available, climate, tectonics and earthquake periodicity (Reading, 1987).

4.2.4 Sphericity, Shape and Roundness

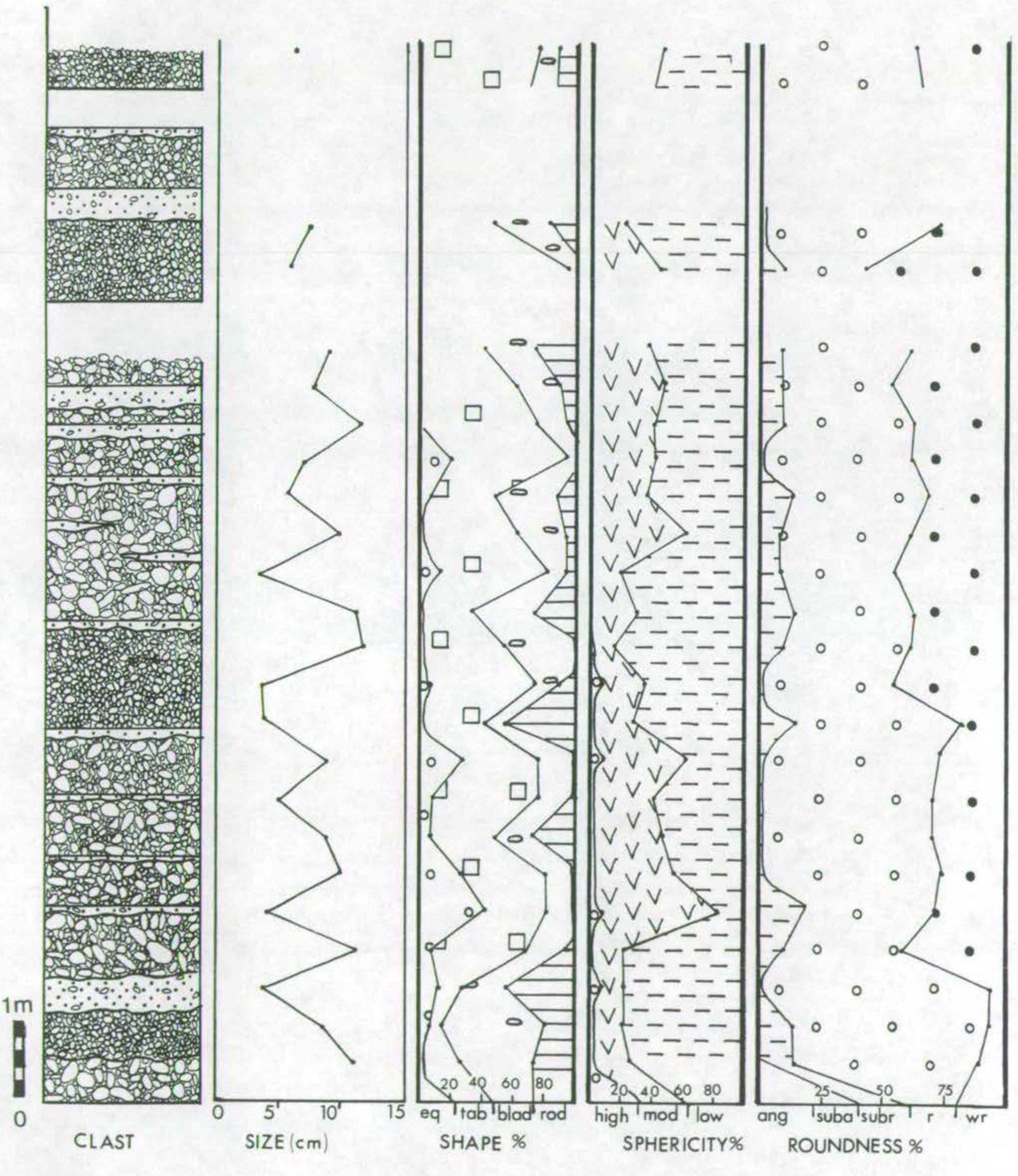
Over 63% of the clasts in the Mulloch Hill Conglomerate are of low-sphericity and 36% of median sphericity (Fig. 4.4). Highly spherical clasts account for only 1%, reflected by the low occurrence of equant shaped clasts (9%). Although clasts are dominantly of low-sphericity, rod shaped clasts account for only 17%, and blade shaped clasts for 27%, so that elongated clasts constitute 44%, slightly less than the tabulate clasts (47%). This illustrates the pitfalls of comparing sphericity and shape of clasts, where sphericity is estimated using visual charts and shape is actually measured using vernier callipers.

At locality 13, the number of rod-shaped clasts decreases upwards. With decreasing size of clasts and increasing distance travelled, it would be anticipated that the number of equant clasts would increase. This is not the case. Perhaps this confirms the observation that abrasion, during transportation, only slightly modifies the shape of a clast. The majority of the clasts fall into the tabulate to bladed category, and the individual units show variations in the number of tabulate to bladed clasts. However, there is a general trend in which there is a decrease in bladed shaped clasts from 47-67% near the base, to 20-30% towards the top of the exposure, corresponding with a gradual increase of tabulate shaped clast from 27% to 60-70% at the top. This is also reflected by a general increase in sphericity, from low- to moderate-sphericity. However, there is no significant change in the number of equant, highly spherical clasts which only account for 1-9%.

4.2.5 Roundness

Up to 60% of the clasts within the Mulloch Hill Conglomerate are rounded. Many of the original faces, edges and corners of the clasts have been smoothed off to rather broad curves, but occasionally they may exhibit broad re-entrant angles between remnant faces. A third of the clasts are well rounded, defined by Pettijohn (1975) as retaining no original faces edges or corners, with the surface consisting of broad convexities and the rest of the clasts possess sub-rounded edges and corners, indicating considerable wear. Variations between the percentages of rounded and well rounded clasts occur within individual units, with the exception of a few anomalies, such as Units 9 and 10 where there is a sudden increase in rounded clasts. There is evidence for declining numbers of subrounded, and rounded clasts and a slight increase in the number of well rounded clasts from 7-13% near the base, to 40-47% towards the top, which accords with the theory that although roundness increases with distance of travel, most rapidly at first and then more slowly, it also increases with time (distance). Perhaps this increase in roundness correlates with the decrease in grain size.

Mulloch Hill Conglomerate Formation (locality 13)



Fig(4.4) Vertical changes in clast size,shape,sphericity and roundness,in the Mulloch Hill Conglomerate Formation,Craighead,(locality 13).

The rounding of the clasts contrasts sharply with the angular grains in the coarse-grained sandstones. Either this is a result of compositional difference and grain size, i.e. the larger the grain, the better the rounding is developed, or the pebbles were rounded prior to deposition.

4.2.6 Clast composition

Clast composition within the Mulloch Hill Conglomerate is varied and includes basic to intermediate igneous rocks and metamorphics.

The igneous clasts include black to grey coloured fine-grained basalts, dark-grey-green coloured medium-grained dolerites, brown coloured andesites, grey to dark grey medium-grained microdiorites and occasionally ignimbrites. Pink granites are very abundant. Metamorphic clasts consist of metamorphic quartz, quartzitic schists, meta-dolerites and green coloured epidote. Chert, red jasper and quartz clasts are also abundant and infrequently very fine-grained siltstones are present.

The diversity in composition indicates a large and diverse source terrain. The source terrain was probably rich in a mixture of plutonic and erruptive igneous and low grade metamorphic rocks, and yet is notably deficient in sedimentary rocks. In order for this level of crust to have been exposed there must have been a major uplift, as confirmed by the occurrence of the granite clasts, which are thought to record rapid erosion of the crystalline basement.

Granite bearing conglomerates, like arkosic sandstone, are thought to be texturally immature since the granite tends to disintegrate. Conditions suitable for granites yielding blocks occur when the disintegration and solution are inhibited or subordinated, usually marked by high relief and rigorous climates (Pettijohn 1975).

4.2.7 Palaeocurrent Directions

Palaeocurrent directions derived from the low-angle and trough cross-bedding indicate that the source lay to the north-northwest.

4.3 NEWLANDS CONGLOMERATE

4.3.1 Description

The beds of the Newlands Conglomerate (locality 55) are unequal in thickness, laterally variable and may be discontinuous (in the sense that the cragged exposure can only be traced for approximately 15m). Commonly bed thickness varies from 0.12m to 2m, reflecting the maximum grain size. The coarser-grained beds are composed of conglomerates, reaching a maximum of 2m thick while the sandstones are much thinner and laterally discontinuous. Average bed thickness is 0.74m.

Since the sandstone beds vary in thickness, are laterally discontinuous (traced for up to 0.3m) and of limited exposure, it was not possible to test for cyclicity.

Pebbles within the poorly sorted conglomerate are small, ranging from 0.5cm to 4.0cm in diameter, whereas the grains in the coarse-grained sandstone average 0.5mm in diameter. Accompanying an increase in bed thickness, there is a marked increase in grain size from the coarse-grained sandstone to the pebble conglomerate, denoting a thickening and coarsening upwards sequence.

As with the Mulloch Hill Conglomerates the pebbles tend to be of low-sphericity, elongated (bladed) to tabulate in shape and subangular to rounded. To some extent the edges and corners of the clasts are rounded off, but secondary corners are numerous. The poor sorting and angularity of the clasts suggests that the clasts have not travelled far from the source.

Composition of the clasts is not as diverse as in the Mulloch Hill Conglomerate. Igneous clasts include altered volcanics, granophyric quartz and metamorphic clasts, represented only by metamorphic quartz. Quartz is abundant, whilst chert and jasper are minor constituents.

The reduction in diversity in clast composition is related to a change in the source area providing the detritus. In particular the source area no longer provided the granites and the other igneous and metamorphic lithologies were limited. Possibly the source terrain (1) had been eroded to such a level that the granite had been eroded away, (2) was further away and since granite is mineralogically unstable it may have disintegrated during a long transportation history (very likely) or (3) there was a slight change in the direction of dispersion of the clasts associated with a change in the location and lithological character of the source.

No cross-bedding was observed, so no palaeocurrent measurements could be made.

The apparent thickening-upward sequence of the Newlands Conglomerate, is attributed to progradation. Normally, progradation occurs in the front of distributary channels of deltas (Fisk, 1955; Coleman & Gagliano, 1965; Rainwater, 1966; Fischer et al. 1970), in alluvial fans and submarine fans. Mutti and Ghibaudo (1972) and Mutti (1974) compared deltaic and turbiditic progradation, correlating the upward transition from prodelta to distal delta front, to proximal delta front deposits, with the succession passing from basinal turbidites to distal outer fan turbidites to proximal outer fan turbidites. In both cases a basin would advance as the result of continued sand supply. Eventually the supply of sand is interrupted, bringing the cycle to an end, when the distributary feeding the lobe is abandoned (Ricci Lucchi, 1975).

4.4 GLENWELLS BURN CONGLOMERATES

4.4.1 Description

Bed thickness in these conglomerates could not be measured because of the poor quality of the exposures in the Glenwells Burn (locality 97). There is a gradual reduction in the pebble size from the first, yielding pebbles of 3.5cm to less than 2cm, in the second conglomerates. Compared with the Newlands Conglomerate, these pebbles tend to be similarly of low-sphericity, being bladed to tabulate in shape, yet more rounded. Furthermore the diversity in clast composition is slightly higher, composed of basalts, dolerites, foliated metamorphic quartz and possibly a few brown coloured fine-grained siltstones in the first conglomerate and cherts, quartz, highly altered volcanic clasts and metamorphic sheared quartz in the second. Though the conglomerates possess different colours, their composition is basically the same. As with the Newlands Conglomerate no suitable structures, such as cross-bedding, crucial for palaeocurrent data were observed.

The exposures of the Glenwells Burn Conglomerate indicate a gradational boundary between the conglomerates and the overlying Newlands Formation. The thickening-upward sequence in the Newlands Conglomerate, succeeded by a thinning upward sequence, traced through the Glenwells Burn Conglomerates into the Newlands Formation, suggests that the distributary feeding the lobe gradually shifted to another position, resulting initially in a prograding, then aggrading sequence.

4.5 UPPER SAUGH HILL GRIT FORMATION

4.5.1 Description

Again bed thickness in the Upper Saugh Hill Grits could not be measured, due to the lack of exposure. At the base, sorting is moderately developed in the pebbly sandstone, with grain size varying from 0.1-0.8cm diameter.

Average pebble size is approximately 0.6cm in diameter. Clasts are of low-sphericity, bladed to tabulate shaped and subangular to subrounded. The clasts are exclusively composed of vein quartz and quartzite.

Quartz is a very stable mineral and its dominance in the pebbly sandstone indicates that the sediment is mineralogically mature and therefore ought to be texturally mature, in that the clasts should be well rounded and highly spherical. Investigations have shown that even in the most mature sands, quartz may show a slight elongation. The shape of the detrital grain is largely attributable to the original growth or fracture (Bloss, 1957; Moss, 1966). Although the gravels are mineralogically mature the associated sands are largely lithic-rich. Because vein quartz and quartzite are very resistant to wear and decomposition, these gravels are of restricted composition. Oligomictic gravels (Schwetzoff, 1934) represent the accumulation of ultra-resistant material. The presence of vein quartz is thought to reflect the destruction of large volumes of igneous and metamorphic rocks, which may have been divided by quartz veins. Consequently they are the residum, winnowed out of a vast body of materials. These deposits tend to occur as sporadic pebbles, commonly less than 1cm in diameter, or as thin pebbly layers at the base of sandstones, or they may recur at several horizons.

Clearly in the Craighead Inlier there is a marked reduction in the diversity of the clast composition from the Mulloch Hill Conglomerate, which yields plutonic, and extrusive igneous metamorphic and possibly siltstone rock fragments, to the Upper Saugh Hill Grits. This traces the gradual erosion of the hinterland supplying the detritus. Near Peebles, Silurian greywackes rich in volcanics also show an increase in quartz content with time (Walton, 1955; and Floyd, 1982).

4.6 CRAIGSKELLY CONGLOMERATE FORMATION

4.6.1 Bed thickness

The conglomerate beds at Craigskelly are unequal and variable in thickness but are laterally continuous. Maximum bed thickness reaches 8.44m, minimum bed thickness is 0.59m and average bed thickness is estimated at 2.12m (Fig. 4.5). Bed to bed thickness varies and there is no median bed thickness (Fig. 4.2).

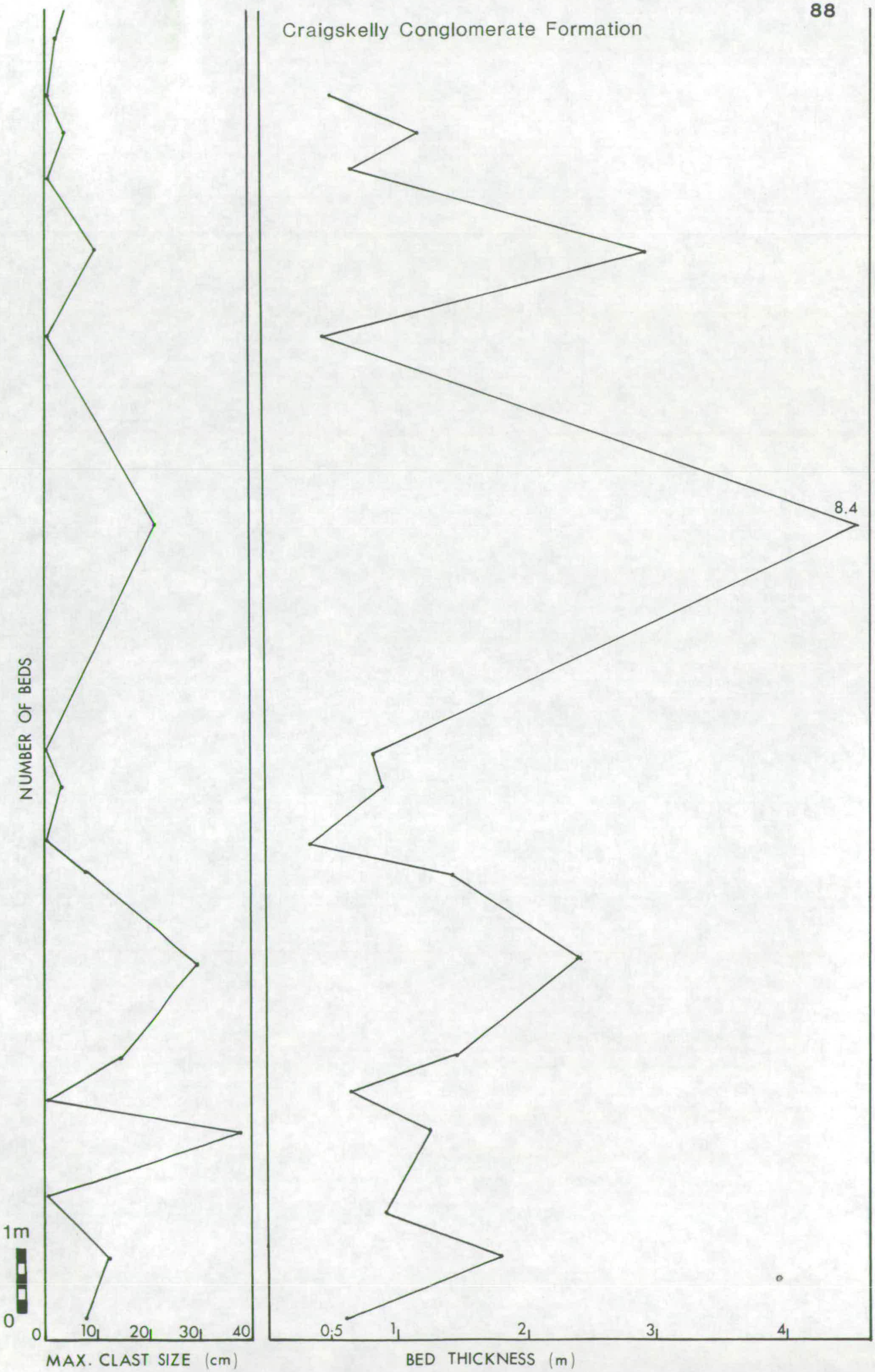
On the other hand, the regularly interbedded sandstones have a distinct lenticular geometry with beds unequal in thickness, laterally variable and discontinuous. As with variations in thickness, the length of the individual units also vary from 3.50m to 52m. With the exception of Unit 12, which can be traced for 32m, it is only towards the very top of the exposure that the sandstone beds can be traced for long distances (Fig. 4.6). Generally bed thickness ranges from 0.22m to 3.20m, averaging 0.48m thick. Unlike the conglomerates, the general bed thickness does not display such a wide spread, with the median (29%) bed thickness occurring between 0.20-0.39m (Fig. 4.3).

Towards the top, it appears that the lenticular sandstone bodies are replaced by more continuous beds which do not display such extreme differences in lateral bed thickness, tending to pinch out gently.

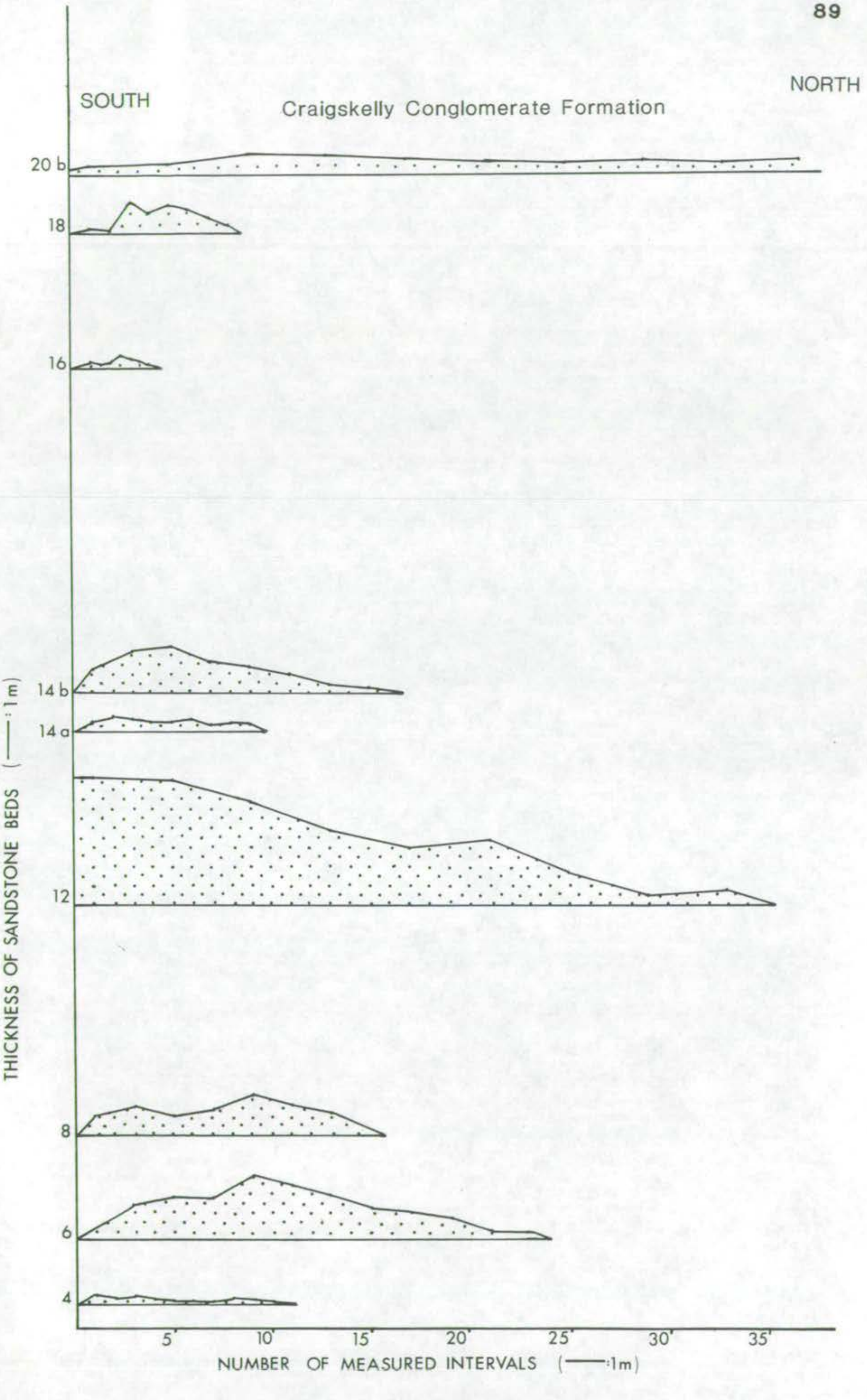
4.6.2 Grain size

Maximum clast size in the Craigskelly Conglomerate is estimated as 41cm diameter, but in general clasts range from 1cm to 15cm diameter, resulting in a poorly sorted texture (Fig. 4.5). Average clast size is 14cm diameter. Within individual units maximum clast sizes fluctuate, notably in Unit 15, where clasts are boulder size, up to 40cm diameter, contrasting significantly with the underlying and overlying pebble-cobble conglomerates.

Fig. 4.5 Vertical changes in bed thickness in the Craigskelly Conglomerate Formation, Girvan Shore (locality 204).



Craigskelly Conglomerate Formation
NUMBER OF BEDS
1m
0
0
10
20
30
40
MAX. CLAST SIZE (cm)
8.4
0.5
1
2
3
4
BED THICKNESS (m)



Fig(4.6) Lateral variations in the sandstone bed thickness,in the Craigskelly Conglomerate Formation,Girvan Shore,(locality 204).

The sandstones vary from very coarse- to coarse-grained, averaging 0.55mm in diameter. Occasionally they have small pebbles (not exceeding 1.0cm diameter) floating in the matrix.

Grain size does visibly influence the bed thickness, in that the much finer lithologies represented by the sandstones are thinner bedded, averaging 0.48m, as compared with the coarser-grained conglomerates, which are thicker bedded, averaging 2.12m thick. Unit 15 is a particularly good example where the cobble conglomerate containing clasts of maximum clast size of 40cm has an approximate thickness of 8.44m thick.

As would be expected the sandstones become gradually finer-grained towards the top of the sequence and thinner bedded. The anomalously thick sandstone lens, Unit 12, occurs in close proximity to Unit 15 and may be related to a minor event, such as a sudden influx of coarse material.

Both conglomerates and sandstones record two megacycles of coarsening- and thickening-upwards, followed by fining- and thinning-upwards cycles. It should be pointed out that there does appear to be a slight increase in clast size after Unit 21. Measurements could not be made because of inaccessibility and danger at the edge of the rugged island.

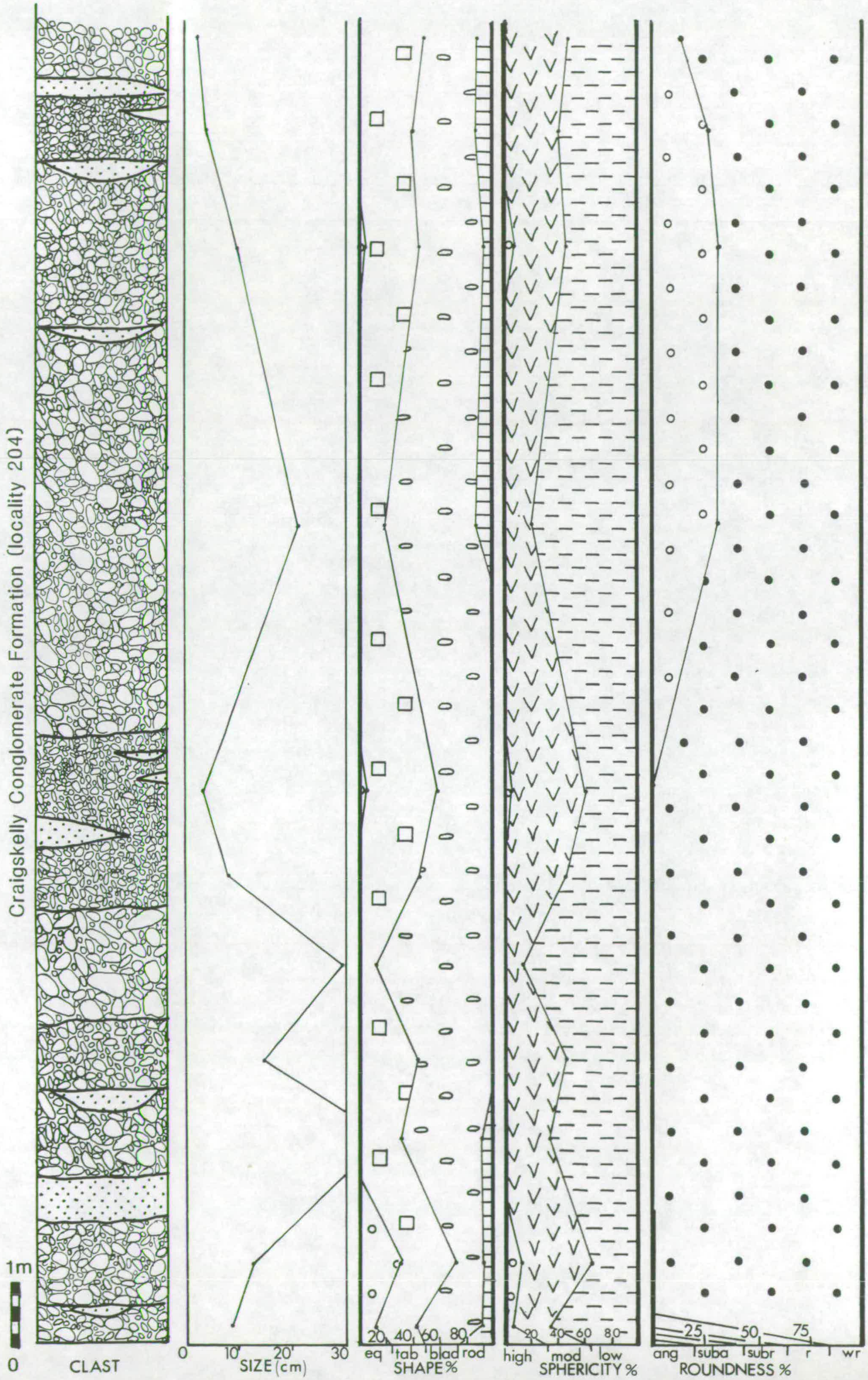
Overall the Craigskelly Conglomerate shows a fining-upward sequence attributed to aggradation. There are sporadic phases when the channel prograded, producing coarsening and thickening cycles. Therefore, whilst the channel was gradually infilling, there were temporary setbacks when there were sudden influxes of very coarse cobbles depositing thick beds, after which there was a return to the main infilling process of the erosional channel.

4.6.3 Sphericity, Shape and Roudness

The majority (cf. 59%) of the clasts within the Craigskelly Conglomerate are of low- sphericity, with moderate-sphericity accounting for 38%, and only 3% highly spherical. Correspondingly, 51% of the clasts are blade shaped, and 6% are rod shaped. Tabulate shaped clasts account for 37%, and only 5% of the clasts are equant (Fig. 4.7).

No simple trend is evident in the evolution of shape of the clasts with time. The lower part of the formation shows minor increases, accompanied by decreases in sphericity. However there does appear to be a moderate increase in sphericity, with low sphericity clasts accounting for 67% near the base, decreasing to 53%. The highly spherical equant clasts, not exceeding 13% in any of the units, tend to occur where the clasts are smaller, for example unit 13 and unit 17. Conversely, where clast sizes are large, such as in unit 10 and unit 15, the clasts tend to be of low sphericity. This observation is supported by the notable increase in blade shaped clasts (unit 15).

Fig. 4.7 Vertical changes in clast size, shape, sphericity and roundness, in the Craigskelly Conglomerate Formation, Girvan Shore (locality 204).


Craigskelly Conglomerate Formation (locality 204)
1m
0
CLAST
0
10
20
30
SIZE (cm)
20
40
60
80
eq
tab
blad
rod
SHAPE %
20
40
60
80
high
mod
low
SPHERICITY %
25
50
75
ang
suba
subr
r
wr
ROUNDNESS %

Correlating with two coarsening- and thickening-, and fining- and thinning- mega cycles, the sphericity and related shapes of the clasts display two phases when the shapes first decrease, and then increase in sphericity. Overall there is evidence of a slight increase in the number of tabulate shape clasts from 33% to 47% near the top. Rounding is very well developed in the Craigskelly Conglomerate such that up to 90% of the clasts appear well rounded, and the rest are rounded. In fact it was very hard to distinguish any variation in roundness within the individual units. It does appear that there is a slight reduction in roundness in unit 15, and thereafter the clast roundness increases. This reduction is related to the influx of the much larger clasts.

4.6.4 Composition

The composition of the clasts within the Craigskelly Conglomerate Formation is very diverse, including igneous, metamorphic and sedimentary rocks (Fig. 4.10). The igneous clasts range from basic to acidic, including andesite, volcanics, dolerite, quartz phyric volcanics, felsite, gabbro, graniteand granodiorite. Metamorphics include schitose quartz, platy slate and yellow coloured epidote. Sedimentary clasts are less abundant comprising reworked conglomerates, siltstones, shale clasts, chert and jasper. Quartz clasts are generally lacking, but at the Horse Rock locality there are some sandstone beds in which small quartz granules (<0.1-0.4cm in diameter) are abundant and display excellent normal grading.

Up to and including Unit 15, which possesses extremely large boulders (40cm) of granite, there is a gradual increase in the number of granite clasts. Thereafter there is a gradual decrease in the number of granite, basic and acidic volcanics, porphyries and conglomerate clasts.

The unusually high percentage of granite clasts and other unstable rock fragments indicates that the conglomerate is texturally immature. The mudstone clasts incorporated into the conglomerate could not have travelled far. Possibly they could have been eroded from the underlying sub-stratum.

If the conglomerates partially reflect the lithology of the source area, it is clear that the diversity of lithologies was high, and the gathering hinterland was large. Not only was the hinterland rich in basic to acidic rocks, and metaquartzites, but there were also some sedimentary rocks.

The quartz rich granular to pebbly layers at the base of some of the sandstones (at the Horse Rock) may be concentrates derived from the destruction of unstable rock fragments.

4.6.5 Palaeocurrent Directions

Low-angle cross-bedding is very rarely developed in the Craigskelly Conglomerate, and thus palaeocurrent data is also scarce. The palaeocurrent data collected from the sandstones show a source from the north or northwest.

4.6.6 Comparison of the Mulloch Hill Conglomerate and Craigskelly Conglomerate Formations

According to Cocks & Toghill (1973) the Mulloch Hill Conglomerate is of *acuminatus* age and is older than the Craigskelly Conglomerate. Neither the Mulloch Hill Conglomerate nor the Craigskelly Conglomerate yield suitable fossils for dating, and consequently their ages can only be estimated by the zone fossils occurring in the immediately overlying formations.

Both the Mulloch Hill and Craigskelly Conglomerates were deposited by similar sedimentological processes, namely debris flows, yielding a succession of poorly sorted clast supported conglomerates, interbedded with coarse-grained sandstones. Furthermore, in each case the exposure has a general lenticular geometry, the conglomerates possess an erosional base where the lower surface of each conglomerate unconformably overlies older Ordovician sediments, thus representing the possible infilling of an erosional channel.

Matrix colour varies between the two, the greyish-red colouration of the Mulloch Hill Conglomerate contrasts with the dusky-green colouration of the Craigskelly Conglomerate. The Mulloch Hill Conglomerate is composed of smaller pebbles and cobble clasts not exceeding 14cm in diameter, whereas the Craigskelly Conglomerate has much larger clasts of pebble to boulder grade, reaching up to 40cm in diameter. Associated with grain size differences, the Mulloch Hill Conglomerates are much more thinnly bedded, ranging from 0.30 to 1.49m compared with 0.50m to 8.40m of Craigskelly Conglomerates. Sphericity values of the clasts are similar, with a dominance of low-sphericity clasts accounting for 63% (MH) and 59% (CC) respectively, and exceedingly few highly spherical clasts, 1% (MH) and 3% (CC). Most of the clasts in the Mulloch Hill Conglomerate are tabulate (47%) to blade shaped (27%) with only a few rod (17%) and equant (9%) shaped clasts. This contrasts slightly with the Craigskelly Conglomerate which has fewer of the end members, the rod (6%) and equant (5%) shaped clasts and more bladed (51%) to tabulate (37%) shaped clasts. Though both conglomerates contain rounded to well rounded clasts the Craigskelly Conglomerates appear slightly better rounded.

Differences are also seen in the composition of the conglomerates. Andesite, dolerites, basalts, feldsites, granites, metamorphic schists, epidotes, quartz, chert and jasper are common to both conglomerates (Fig. 4.9 and 4.10). However, sedimentary clasts seen in the Craigskelly Conglomerates are lacking in the Mulloch Hill Conglomerate, particularly reworked conglomerate clasts and mudstone clasts. Furthermore, quartz clasts are more abundant in the Mulloch Hill Conglomerate.

Structures are generally lacking in the conglomerates. The Craigskelly Conglomerates do show evidence of imbrication, preferred alignment of the clasts, and reverse grading is only obvious in the Craigskelly Conglomerate.

Each formation has poorly sorted, very coarse- to coarse-grained sandstones, regularly interbedded with conglomerates and the thickness of these beds varies laterally, tending to thin out. The sandstones of the Mulloch Conglomerate are more laterally extensively traced for up to 50m, and are thinner bedded, ranging from 0.09 to 0.49m, compared to a bed thickness range of 0.20 to 3.30m in the Craigskelly Formation, which have a specific lenticular shape.

The bases of the sandstones are irregular and graded, whereas the tops tend to be sharp. The Mulloch Hill Conglomerate has significantly more pebbles floating within the matrix, whilst the Craigskelly Conglomerate sometimes displays concentrations of quartz granules at the base of the sandstones, which fine upwards. Laminations in both conglomerates are defined by grain size variations, and low angle cross bedding is common to both. Towards the top of the Mulloch Hill Conglomerate exposure (locality 13) however, trough bedding is overlain by parallel laminated sandstones. Palaeocurrent analyses for both conglomerates are fairly similar and indicate a source area to the north, which shed debris to the southeast.

Perhaps the most significant difference is the occurrence of the thinly bedded sandstone in the middle of the Mulloch Hill Conglomerate. This is the only place where fragmented fossils including brachiopods and crinoid ossicles were found, contrasting with the unfossiliferous Craigskelly Conglomerate.

Discussion

It is concluded that the Mulloch Hill Conglomerate and Craigskelly Conglomerate are dissimilar although they were deposited by similar processes, namely debris flows, and represent the gradual infilling of shallow water erosional channels. The variations may be the result of major age differences. It is assumed that the two conglomerates accumulated in two separate areas. Owing to the absence of suitable zone fossils it cannot be determined with certainty which conglomerate is the older. According to Cocks and Toghill's (1973) biostratigraphical correlations, the Mulloch Hill Conglomerates are in fact older than the Craigskelly Congomerates. On the basis of sedimentological evidence such as the smaller clast size, the thinner beds, the laterally more continuous beds, the reduction in less stable rock fragments, and the development of parallel laminations overlying cross-bedding, it appears that the Mulloch Hill Conglomerate, although a proximal deposit, was deposited slightly further away from source than the Craigskelly Conglomerate.

Both conglomerates shared the same general source area located approximately north to northwest, providing a diverse assemblage of lithologies including basic to acidic igneous rocks and granites, metaquartzites and a few sediments. Slight variations in composition of the clasts may either relate to local variations in the source area or to the distance from the source.

4.7 HAVEN CONGLOMERATE

4.7.1 Bed thickness

In the Haven Conglomerate (locality 217) the conglomerate and sandstone-beds are generally unequal and laterally variable in thickness, but the sandstone beds tend to be discontinuous.

4.7.2 Grain Size

Grain size varies from 2.0cm to 50.0cm, averaging 6.0cm in diameter in the poorly sorted conglomerates, whilst the sandstones are coarse- to medium-grained (0.3mm in diameter). Despite minor fluctuations in grain size there does appear to be an overall decrease in grain size from 21.0cm diameter to 2.0cm diameter towards the top. Infrequently, anomalously large clasts (up to 28cm in diameter), composed of bioclastic siltstones, occur in the higher parts of the sequence.

4.7.3 Sphericity, Shape, Roundness

The clasts are generally of low- to moderate-sphericity (57% and 40% respectively) and this is reflected by clast shape where rod and blade shaped clasts are abundant (17% and 40% respectively) and equant clasts are extremely scarce accounting for only 1%.

As compared with the Craigskelly Conglomerate rounding is poorly developed. Up to 90% of the clasts are angular to subangular, showing little evidence of wear and possessing sharp edges and corners. Normally this would indicate texturally immature sediments, which have not travelled far from the source. The high percentage of angular grains is correlated with the high percentage of quartz clasts. Since quartz is very stable and hard, it has a high resistance to rounding. The more rounded clasts tend to be composed of softer rock fragments such as dolomite and siltstones.

4.7.4 Clast composition

The Haven Conglomerate heralds a sudden influx of quartz, producing a very quartz-rich conglomerate (Fig. 4.10). The porphyry clasts seen in the Craigskelly

Conglomerate are absent, and there is a marked reduction in the diversity of basic to acidic igneous clasts. Other constituent clasts comprise dolomite clasts, chert, jasper, metaquartzites, mica schists, shale and bioclastic siltstones from the underlying Woodland Formation.

Clast composition is less diverse and therefore it is inferred that there was a marked reduction in the diversity of source lithologies. High quartz content is consistent with highly mature accumulations of ultra resistant material. Where there are distinct concentrations of quartz grains, the other less stable rock fragments may have been disintegrated leaving behind the residual quartz clasts. The anomalously large shale clasts were derived from the erosion of the underlying Woodland Formation and therefore do not originate from the hinterland. The appearance of dolomite pebbles and cobbles suggests that some kind of carbonate bank developed at the top of the slope.

4.7.5 Palaeocurrent Data

No suitable sedimentary structures were found, during this investigation, to ascertain the palaeocurrent direction. Bluck (1983) however, records a northeast-southwest trending palaeoflow indicating that the source lay to the northeast.

4.7.6 Comparison of Newlands Conglomerate with the Haven Conglomerate

Both the Newlands and Haven Conglomerates were deposited by debris flows, producing conglomerates and sandstones. Superficially they appear very thickly bedded, yet when examined closely they do have finer, laterally discontinuous, sandstone beds. Clasts within the Newlands Conglomerate are much smaller, i.e. reaching a maximum of 5cm, compared with 50cm diameter in the Haven Conglomerate, and the latter displays a better fining-upward sequence. Quartz is dominant in both, with minor amounts of basic igneous rocks, chert and jasper (Fig. 4.9 and 4.10). Unlike the Haven Conglomerate there is no evidence in the Newlands Conglomerate of clasts eroded and incorporated from the underlying sediment, nor are dolomite clasts present. Neither of the sandstones displayed cross-bedding, nor were they fossiliferous.

4.8 SCART GRIT FORMATION

4.8.1 Bed Thickness

The beds in the Scart Grits (locality 225) are equal to subequal in thickness, laterally uniform in thickness and continuous. Bed thickness ranges from 0.09m to 2.54m and average bed thickness is estimated as 0.57m thick (Fig. 4.8). The spread of bed thickness is wide and the median (17%) bed thickness is between 0.20 and 1.29m thick (Fig 4.2 and 4.3).

Fig. 4.8 Vertical changes in bed thickness in the Scart Grit Formation, Girvan Shore (locality 225).

FIGURE 4.8

Scart Grit Formation (locality 225)

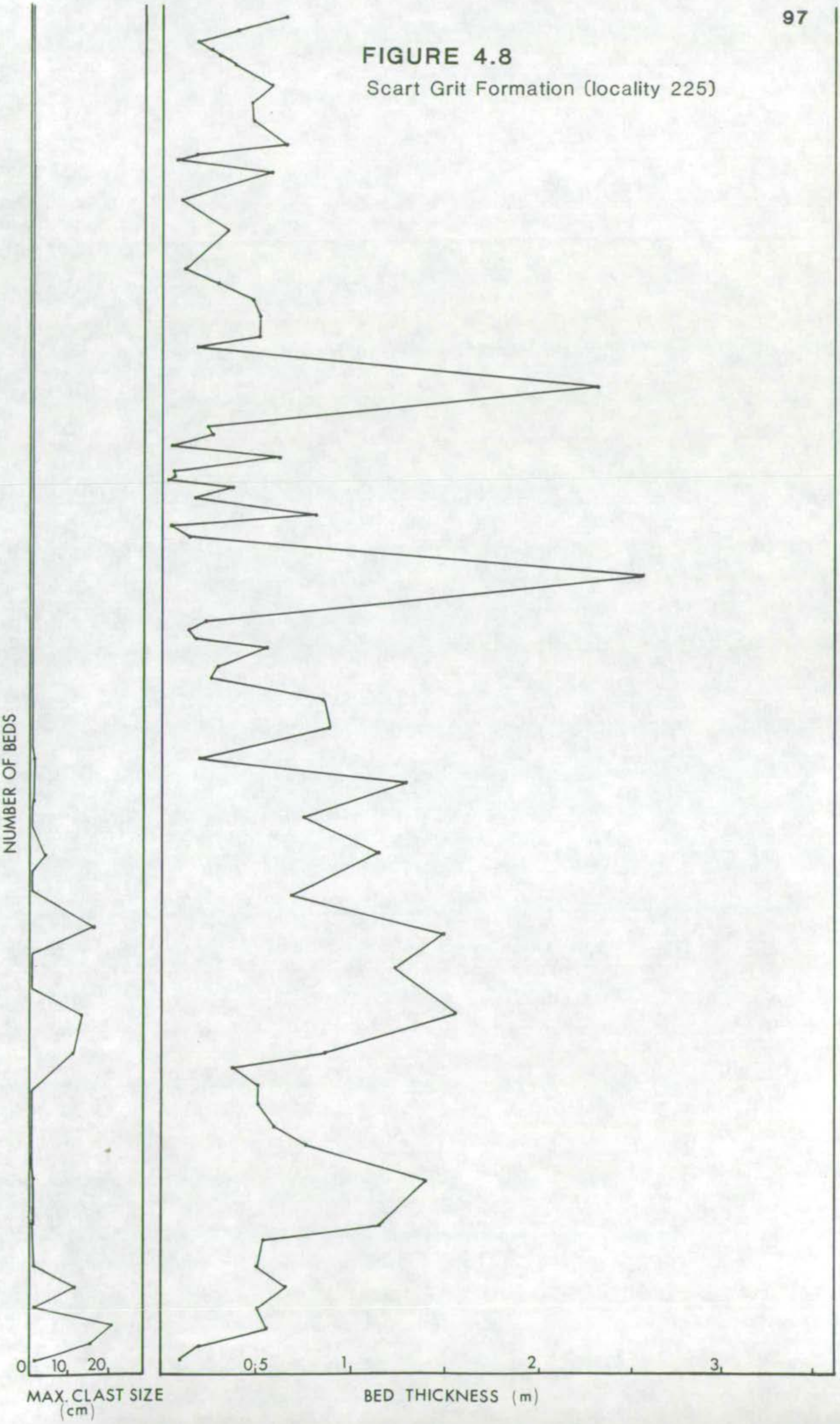


FIGURE 4.9

FORMATION	IGNEOUS CLASTS	METAMORPHIC	SEDIMENTARY
U. Saugh Hill Grit Fm.	Quartz Chert	Quartzite Mica schist	
Glenwells Burn Conglom. 2	Altered volcanic clast Chert Quartz	Quartzite	
Glenwells Burn Conglom. 1	Basalt Dolerite Jasper Quartz	Quartzite	Siltstone
Newslands Conglom.	Altered volcanic clast Chert Quartz Jasper	Quartzite	
Mulloch Hill Conglom. Fm.	Basalt Dolerite Pillow lava Andesite Micro-diorite Ignimbrite Granite Chert Jasper	Quartzite Meta-dolerite Epidote	Siltstone

Fig(4.9) Composition of some of the clasts in the conglomerates of the Craighead Inlier.

FIGURE 4.10

FORMATION	IGNEOUS CLASTS	METAMORPHIC	SEDIMENTARY
Scart Grit Fm.	Feldspar rich volcanics Andesite ? Dolerite Chert Quartz	Quartzite Mica schist	Siltstone Dolomite Criniodal limestone
Haven Conglom.	Volcanic clast Basalt Lava Jasper Quartz	Quartzite Mica schist	Siltstone Dolomite Shale
Woodland Fm.	Dolerite Chert Quartz	Quartzite	Siltstone Dolomite
Craigskelly Conglom. Fm.	Volcanic clast Quartz phyric volcanic clast Granite Granodiorite Gabbro Jasper Serpentinite Chert Quartz	Quartzite Platy slate Epidote	Siltstone Conglomerate Shale

Fig(4.10) Composition of some of the clasts in the conglomerates of the Girvan Shore.

4.8.2 Grain Size

Towards the base of the exposure there are a number of pebbly sandstones and pebbly conglomerates, with clasts ranging from 1cm to 19cm, averaging 5.8cm in diameter (Fig. 4.8). Apart from slight fluctuations in pebble size there is a gradual reduction in clast size and grain size, passing from pebbly sandstones to coarse- to medium-grained sandstone, and towards the top siltstone horizons are developed.

Correspondingly there is a gradual reduction in bed thickness from over 1.5m to 0.50cm, tracing the slow aggradation of the channel.

However this simplified trend masks the thickening- and thinning-minor cycles, which may be related to changes at the point of supply, such as variations in the amount and grain sizes available.

4.8.3 Sphericity, Shape and Roundness

Most of the clasts are of low-sphericity (67%) and moderate-sphericity (33%), reflected by the dominance of blade and rod shaped clasts (40% and 27% respectively). Over half the clasts are angular to subangular with 45% subrounded and 2% rounded. There is no significant change in the shape or roundness, moving up the sequence.

4.8.4 Composition

Clast composition in the Scart Grits is more diverse than the Haven Conglomerate, a fact heralded by the reappearance of granite and a slight increase in fine-grained igneous clasts, feldspar rich volcanics, andesite and dolerite and chert clasts (Fig. 4.10). Quartz is not as abundant as in the Haven Conglomerate, but in some places coarse-grained sandstones are dominated by quartz granules. Metamorphics are represented by mica schists and quartz schists. Bioclastic Woodland Formation siltstones are far less abundant as are reworked conglomerate clasts, whilst orange dolomite clasts are still prominent. One interesting addition to the general assemblage is the appearance of crinoidal limestone clasts. Apart from these minor modifications to the clast composition, there does not appear to be a dramatic change in the source area from that which provided the rock fragments for the underlying Haven Conglomerate.

4.8.5 Palaeocurrent Data

Palaeocurrent data from low-angle cross-bedding is supplemented by measurements made on flute casts on the soles of the sandstone beds, indicating that the provenance lay in the northeast.

4.9 SOURCE OF THE CLASTS

Although the composition of the clasts in the conglomerates at Craighead, and at the coast reflects the lithology of the source area and palaeocurrent data shows that the sediment was derived from a northerly source, the actual location of the source area during the duration of the Silurian remains uncertain.

Much work has been carried out on the various conglomerates occurring throughout the Silurian sequence. In the Llandovery, conglomerates are sporadic, whereas in the Wenlock there are two laterally persistent bands - the 'igneous conglomerate' conventionally taken as the base of the Wenlock, (McGiven, 1967; Rolfe and Fritz, 1966; cf. Cocks et al., 1971 fig 6) and the quartzite conglomerate of Peach and Horne (1899, p579). Near the Silurian-Devonian boundary, a third conglomerate is characteristically rich in greywacke clasts. The Llandovery conglomerates in Girvan contain a similar assemblage of igneous clasts as are found in the 'igneous conglomerate.' The lower 'igneous conglomerates' are interpreted as recording the influence of ophiolites and other rocks, whilst the quartz rich conglomerates may represent second cycles from the Ordovician (Walton, 1983).

Leggett et al. (1979, fig 8), Leggett (1980, fig 3) and Leggett et al. (1982, fig 7) postulate that the source area lay to the south of the present outcrops, namely the rocks of the Southern Uplands. According to their hypothesis the Ordovician trench deposits were uplifted into a trench slope break, which provided detritus to the trench system to the southwest and a fore-arc basin to the northwest. Walton (1983) also argues that the source shed debris to the trench, in the southeast, referring to the source land as the Silurian "Cockburnland". "Cockburnland" is recognised as a 'tectonic ridge.' Ziegler (1970) separated the lower trench slope from the upper slope basin, suggesting that it may have occupied much of the southern half of the Midland Valley (McKerrow et al. 1977). It has been proposed that the present Ordovician outcrop of the Southern Uplands represents this Cockburnland (during the Llandovery-Wenlock times) (Leggett, 1980 fig 3; Leggett et al., 1982 fig 6). The regional setting of the much argued Midland Valley will be discussed in Chapter 10.

It has been suggested that the acidic lava clasts originated from the Tweedale lavas whilst the granite clasts come from the Ordovician conglomerates (fig 3 Walton, 1956; Kelling, 1962; Kelling and Holyrood, 1978). The Ordovician rocks of Tweedale comprise mainly greywackes, with conglomerates, siltstones, shale, chert and basic intermediate to acidic rocks (Eckford & Ritchie, 1931; Thirlwall, 1981a).

Bluck (1983) however points out a number of irregularities undermining the concept of a mixed provenance:

1) The Silurian 'igneous conglomerates' stretch from North Esk to the Hagshaw Hill Inliers, whilst the Tweedale lavas are restricted to a small tract near Peebles (Eckford & Ritchie, 1931 fig 1).
2) The igneous clast assemblage is similar in both the 'igneous conglomerate' (Wenlock) and the Girvan Llandovery conglomerates, even though the former has palaeocurrent data from cross-strata and flute marks indicating a source area to the southeast (McGiven, 1967) whilst the Girvan conglomerates were derived from the northwest.
3) Basic igneous rock fragments including dolerite, gabbro and lavas are abundant in the granite bearing Ordovician conglomerates (fig 3 Walton, 1956; Kelling, 1962) but do not appear to be as abundant in the Silurian conglomerates.
4) Furthermore, whilst vein quartz is common in the Ordovician conglomerates, it is relatively deficient in the Silurian conglomerates.
5) Ordovician greywackes are also few in the Silurian conglomerates. In the Ordovician sequence, basic and feldspar rich and 'silic' greywackes are closely interstratified with each other (Floyd, 1982 table 1). However the greywacke clasts from the Silurian Conglomerates are rich in quartz ansd silic fragments, resembling some of the Ordovician greywackes or Southern Uplands (Floyd, 1982; Hepworth et al., 1982) and Silurian greywackes (Warren, 1963, 1964).
6) If the Ordovician greywackes and conglomerates are the source of the Silurian conglomerates it is hard to explain the marked vertical change in the composition through the Silurian succession from igneous rich conglomerates to vein quartz and quartzite-rich conglomerates occurring near the base of the Middle Wenlock. Although the quartzite clasts are associated with the granite clasts in the Southern Upland conglomerates, granite clasts are rare in the Silurian 'quartzite' conglomerates.

Bluck (1983) argues against an Ordovician source for the conglomerate, because

1) The roundness values for Silurian clasts in the Llandovery conglomerates and igneous conglomerates are arguably higher or lower.
2) It is not thought possible that the Tweedale lavas provided the debris for the Llandovery conglomerates in Girvan (because the Llandovery conglomerates of Girvan have a southeast or east Dispersal) and it is unlikely that such a small tract of land could supply debris to the 'igneous conglomerates' from North Esk to the Hagshaw Hills.
3) Conglomerate clasts in the Silurian conglomerates (for example in the Craigskelly Conglomerate) are richer in acidic clasts than the Ordovician conglomerates.

Bluck concludes that the Silurian Cockburnland did not comprise the Ordovician rocks of the Southern Uplands, and does not consider it to have been an upper trench-slope-break. The Silurian conglomerates of Girvan have a source composed of acidic-intermediate igneous rocks, metaquartzite rocks, and conglomerates with a north, northwest or west derivation and the other inliers are thought to have also shared this type of provenance, but during Wenlock times the conglomerates were dispersed from the south or southeast.

The source of these later conglomerates is postulated as lying south of the Ordovician outcrops where Wenlockian or younger trench deposits outcrop now. Either the Southern Uplands were covered by other formations which supplied the detritus to the north and northwest or they were not in that position during the Silurian. The provenance area may have been a southerly extension of the Midland Valley which is now buried beneath the allochthonous Southern Uplands. By comparing Cockburnland (represented by the Ordovician outcrops of the Southern Uplands) which has a maximum width of c.26km (decreasing northeast to 100m) with the present day Sunda fore arc basin varying between 60-80km, Bluck (1983) advocates that there is a missing fore arc sequence though lateral movement along strike faults (e.g. Elders, 1987) could equally have removed the missing source area.

It is evident that the Silurian deposits accumulated in a basin which received debris initially from the north, and subsequently the sedimentary supply was principally from the south. A northerly location is also envisaged for the marine Caradoc-Llandovery deposits of the Pomeroy and Lisbellaw Inlier, in counties Tyrone and Fermanagh, Northern Ireland (Simon, 1986). These deposits have a similar setting and dispersal to the Llanvirn-Wenlock deposits of the Girvan area and may have shared a similar provenance. Principally the Pomeroy and Lisbellaw conglomertes are rich in quartzite, vein quartz, granite, jasper and minor amounts of welded tuffs and porphyries (Simon, 1986) differing from the Girvan conglomerates which contain a more abundant and diverse igneous clasts of granite, volcanic and hypabysal rocks reflecting differences in the age or evolutionary history of the rocks comprising the source area.

Unlike the younger Silurian deposits of the Southern Midland Valley, there is no evidence of a southerly source or a ridge separating the rocks deposited in the Irish Silurian Inliers from the accretionary prism, therefore, Simon (1986) suggests that there is no evidence for extending Cockburnland west of Scotland.

Discussion

Paleocurrent data in the Craighead Inlier is scarce but the general south east orientated azimuths coincide generally with similar orientations measured from the coastal sections south of Girvan. Consequently it is assumed that the same source shed debris to both areas, although there were slight local variations in clast composition for example, the presence of reworked conglomerates, dolomite and shale and trinoidal limestone clasts in the coastal conglomerates. If the source area was in the northwest then the lavas could not have been derived from the Tweedale lavas. In agreement with Bluck's observations both the Craighead and Girvan Inliers were supplied by a source in the north or northwest which comprised acidic to basic igneous rocks, metaquartzite rocks and a minor suite of sedimentary rocks including conglomerates, dolomites and siltstones.

Further research into the conglomerates at Craighead, and particularly at the coast involving isotope dating of the granite clasts and comparison with rocks north of the Inliers, would not only be very rewarding but may help in identifying the source area and resolve the controversy over the tectonic elements and their relative position of tectonic settings of Midland Valley.

CHAPTER 5

5.0 PETROGRAPHIC DESCRIPTIONS OF THE SEDIMENTS IN THE CRAIGHEAD INLIER

5.1 INTRODUCTION

Petrographic studies of sediments are of great value for the interpretation of the environments in which they were deposited. Initially they convey important information on the detailed composition of the rocks, allowing deductions to be made about the lithology and the tectonic history of the source area which provided the detritus.

Petrographic studies also provide data on grain-size, sorting and rounding of sedimentary grains which is instrumental in the determination both of transport directions and the depositional environment. Finally, they afford important information on post-depositional, alteration history of the rock (for example, compaction, fracturing and cementation). All this information contributes to a deeper understanding of the geological history of the area studied.

5.1.1 Grain size

Grain size is largely dependent on particle size and current strength in the local environment (Folk, 1968). It is safe to assume that sediments become finer-grained in the direction of transport. This is partly a result of abrasion. Whereas reduction in the size of pebbles is due to chipping and rubbing, it is thought that very little reduction in the dimension of sand-sized quartz grains is actually effected through transportation. Thus the difference in size is due to selective sorting by which the smaller grains outrun the larger, heavier ones in a downcurrent direction. The sorting of the sediments depends on numerous factors, such as the range of available particles, the mode of deposition and the current characteristics.

5.1.2 Sphericity

Sneed (Folk, 1968) recognised that the main control on sphericity and form is pebble lithology (for example chert and quartz are extremely hard and thus resistant to abrasion) together with internal anisotropism such as bedding, schistosity and the original shape of the particle. Roundness results from a combination of chipping and rubbing of very small particles. Softer grains will round faster and harder grains, such as quartz, will remain fairly angular. Furthermore coarser grains round more easily because they are not cushioned by a water film and thus impact vigorously with each other. Cleavage also plays an important role because large grains possessing good cleavage tend to fracture readily.

In sedimentary rocks, the composition and abundance of terrigenous debris hinges on three main factors 1) availability of minerals present in the source area, 2) mechanical durability, favouring hardness and lack of cleavage and 3) chemical stability.

5.1.3 Maturity

Sediments may be classified according to their mineralogical and textural maturity. Mineralogically mature sediments contain a high percentage of chemically stable and very hard, physically resistant minerals such as quartz, chert and ultrastable minerals (e.g. zircon). Feldspars are softer than quartz, and possess a much better cleavage hence abrasion reduces their size and increases roundness much more rapidly. Thus mineralogically immature sediments are those containing less stable grains such as feldspar and rock fragments.

Textural maturity is defined by the proportion of fine-grained material, the sorting and the roundness of the grains. Folk (1951) proposed a scheme of textural maturity ranging from immature to supermature stage. The former is characterised by a sediment having more than 5% clay matrix, composed of poorly-sorted and not well rounded grains, whilst the latter, the supermature sediments, contain no clay but are composed of well-sorted and well-rounded grains.

Textural maturity is thought to be associated with the environment. Some workers claim that it is actually a direct function of tectonism, in that intense tectonic activity with rapidly subsiding basins yields stratigraphic sections of immature sediments, whereas mildly unstable areas (associated with unstable shelves) produce all the submature sediments, and the most mature sediments are associated with stable conditions, linked with stable shelves. Folk (1968) believes that this is a gross over simplification, arguing that the environments of deposition exert much greater control than tectonism on the sorting and rounding of the sediment. Subsequently he concluded that textural maturity of sandstones is dependent on environment, while the volumetric importance of specific environments is determined by tectonic activity. Krynine (1942) showed that the degree and type of tectonic activity does determine a certain preferred association of source area lithology, relief, geomorphic processes and rate of subsidence of depositional basin. Additionally the mineral composition is controlled by the source area lithology which is also affected by tectonism. The most immature rocks may, therefore, be formed during periods of crustal unrest, and will be rich in unstable constituents such as metamorphics, micas and feldspars.

5.1.4 Craighead Inlier

The account below gives detailed descriptions of the major lithologies present in each formation, for the Craighead Inlier and for the coastal sections, respectively. Since proper identification of the framework grains is the key to classification of sedimentary rocks, point counts were measured for the coarsest sediments. In the Craighead Inlier these are the Mulloch Hill Conglomerate, the Newlands Conglomerate, the Glenwells Burn Conglomerate 1, Conglomerate 2, and the Upper Saugh Hill Grits. In the coastal sections they include the Craigskelly Conglomerate, the Haven Conglomerate and the pebbly sandstone at the top of the Scart Grits. Three hundred grains were point counted from ten thin-sections, and allocated to one of nine parameters. Krynine's (1946) genetic classification of quartz types was utilised for subdividing the quartz into quartz and rock fragment quartz from igneous and metamorphic sources. Quartz derived from metamorphic sources was considered as representing rock fragments.

Degree of sorting and descriptions of grain shapes and roundness were estimated visually using Pettijohn et al.'s (1973) diagramatic charts, and grain size was measured to the nearest 0.01mm.

Many of the lithologies in the Craighead Inlier and the coastal section resemble greywackes. For many years the term 'greywacke' has caused controversy, not only with respect to the origin of the named rocks, but also to the definition of the term. As a result there is a wealth of literature dealing with the various definitions including Allen, 1936; Bailey, 1930, 1936; Bosewell, 1960; Cummins, 1962; Edwards, 1947a, 1947b; Fischer, 1933; Folk, 1954; Helmbold, 1952; Krynine, 1940, 1941, 1948; McBride, 1962; McElroy, 1954; Naumans, 1858; Pettijohn, 1943, 1950, 1954, 1960; Tyrell, 1933 and more recently Dott, 1964 summarised the nomenclatural problem which was reviewed by Okada (1971) and Pettijohn et al. (1973).

Application of the term 'greywacke' was applied by Lasius (1789) to sandstones of the Upper Devonian-Lower Carboniferous strata of the Harz Mountains in Germany, but prior to this, the term was used by Werner (1787) (Crook, 1970). Thirty years later Jamieson introduced the word to the English speaking world and used it for similar rocks of lower Palaeozoic age in the Southern Uplands of Scotland. Differences of opinion concerning the correct definition of greywacke multiplied so rapidly that by 1854 Murchison suggested that it be abandoned. More recently Helmbold (1952) and Mattiat (1960) restudied the Harz Mountains. Typically 'greywackes' are distinguished by their dark grey colour, and by their assemblage of unstable minerals (more than 15%) including feldspar and sand-sized rock fragments, bound in a fine-grained matrix (of sericite, chlorite, quartz and feldspar) which takes the place of the chemical cement.

The quantitative definition of the term greywacke has caused a lot of disagreement as to the precise location of the boundaries between greywackes and other rocks into which they grade. The matrix is essential to the definition and allocation of the term. Okanda (1971) uses a spectrum from 5 to 25% matrix to distinguish between a 'wacke' from a clean sandstone, whereas Doff (1964) and Williams, Turner & Gilbert (1954) used 10% as a marker. Generally most workers have chosen 15%.

It is important to remember that the original definition was established nearly 70 years before the invention of the polarising microscope. Thus the term was initially defined and applied on the basis of field observations to dirty, dark, clay-rich muddy sandstones, but historically does not really take into consideration the composition. Moreover greywackes have now become virtually synonymous with turbidites. Since the term is still imprecisely defined it is here preferred to abandon the word and instead to apply the name lithic arenite.

5.1.5 Cathodoluminescence

Within the last 20 years CL has become increasingly important in sedimentary petrography, providing additional information to observations made with transmitted light. Miller (1988) and Marshall (1988) point out a range of CL applications including swift identification of the constituent minerals, particularly when dealing with fine-grained sediments or where minerals display similar optical properties; fabric and textural characteristics can be better visualised enhancing the history of cementation and diagenesis. CL also affords invaluable data for provenance studies; grain origin can be broadly determined; specific grain suites with characteristic CL signatures can be related to their source rock, so mixing of grains from different source areas can be determined (Stow and Miller, 1984).

The CL colour and brightness depends upon a number of factors, such as the beam voltage, current, nature of the sample surface, degree of heating and geochemical composition of the sample.

5.2 DESCRIPTIONS AND INTERPRETATIONS

5.2.1 Mulloch Hill Conglomerate Formation

Section Nos: TW.13.141, TW.13.142, TW.13.143, and TW.13.145

Type: Very coarse-grained lithic arenite

Locality: 13, Craighead

Description:

This very poorly sorted rock consists of a coarse- to medium-grained aggregate of quartz (c. 19%), lithic fragments (c. 45%), feldspar (c. 3%), opaque minerals (c. 8%) and mica (c. 1%) grains, cemented dominantly by authigenic quartz and set in a matrix of clay (Figs 5.1 and 2, and Plate 3.1.1 and 3.1.2).

FIGURE 5.2

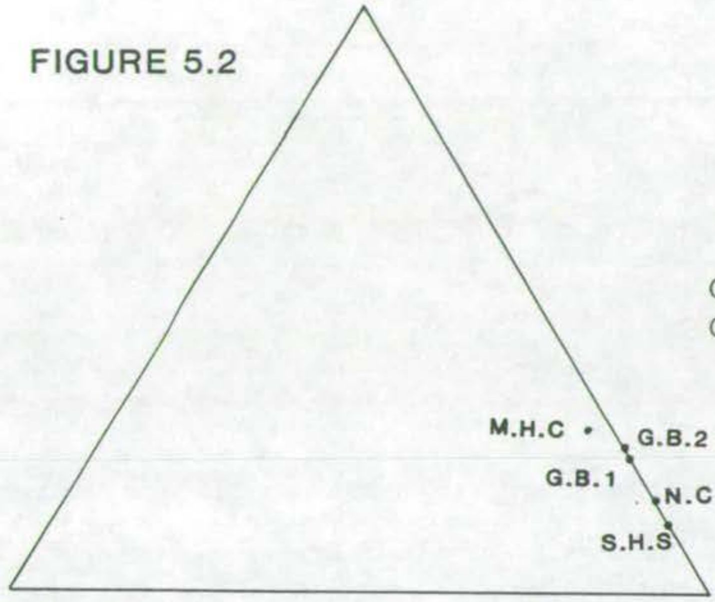
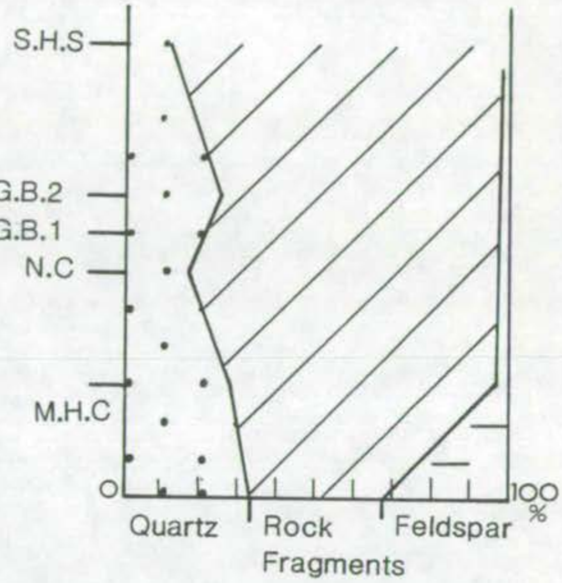


FIGURE 5.3



Fig(5.2) Constituents of the Formations plotted on a ternary diagram (Q.F.R).

Fig(5.3) Vertical change in the percentages of Quartz,Rock Fragment and Feldspar content.

FIGURE 5.1

Constituents	Formations					
	M.H.C	M.H.C	N.C	G.B.1	G.B.2	S.H.S
Quartz	19	8	11	13	10	9
Rock Fragments	45	60	59	50	33	66
Feldspar	3	1	0	1	0	0
Oxide	8	5	0	2	8	1
Quartz Cement	2	0	7	0	0	2
Mica	1	5	0	4	6	9
Clay	21	19	23	23	43	13
Calcite Cement	0	0	0	6	0	0
Porosity	0	0	0	0	0	0
Olivine	0	2	0	0	0	0

Fig(5.1) Table of constituent percentages of very coarse-grained sandstones (300 point counts per thin section).

The original clastic quartz grains range in size from 0.2mm to 12.00mm diameter (sand to gravel grade) but average approximately 1.0mm diameter (very coarse sand grade) varying from elongate to tabulate, and generally of low sphericity. The majority of the grains are sub-angular to sub-rounded. The monocrystalline plutonic-type quartz crystals show both uniform and undulose extinction and contain vacuoles, often concentrated into lines (Plate 3.1.3). Occasionally, sub-parallel lines of very small bubbles, (Boehme lamellae) are seen in the quartz which are thought to be the product of intense strain deformation. Composite quartz occurs as the 'recrystallised metamorphic' quartz type of Drynine (1940). The crystal boundaries are straight and crystal shapes are slightly elongate and characteristic of quartz grains of high-grade metamorphic origin. Other types of quartz thought to be of metamorphic origin in the Mulloch Hill Conglomerates are polycrystalline quartz composed of fairly equant grains, with straight to slightly undulose extinction and irregular, crennulate boundaries between strongly elongate grains (equivalent to Krynine's 'schistose'). Diversity and abundance of lithic fragments is high; they consist of a mixture of metamorphic and igneous clasts (Plate 3.1.4). Foliated, metamorphic quartz or quartzitic schists have been described above. One large clast, containing actinolite chlorite, and possibly albite and quartz may be a metadolerite which has been highly altered, associated with greenschist facies metamorphism. In addition single crystals of yellow to green epidote are up to 0.75mm in size.

Generally the igneous rocks occur in the basalt to andesite spectrum. Fine-grained basic igneous rocks are dominant, specifically basalts composed essentially of calcic plagioclase and pyroxene. Some are altered to glass, associated with very rapid cooling, and this rapid rate of cooling is also reflected in one clast, basaltic in origin, possessing a relict oxide rim-coating. Possibly this clast may be a pillow lava. Low-grade metamorphism is responsible for the alteration of the feldspar. There are also coarse-grained basic rocks of doleritic affinities; containing long lenticular feldspars with variolitic textures, arranged in fan-like, starry aggregates and there are also gabbros. There are a few clasts which resemble andesites and their coarse-grained equivalents, namely microdiorites.

A few vesicular volcanic rock-clasts are present in the conglomerate. One highly birefringent clast displays an amygdaloidal texture. In this particular case there are two phases of cavity filling - the centre of the amygdale is composed of chlorite and is surrounded by a thin rim of quartz. Furthermore a large elongated clast may originally have had a rhyolitic composition but now resembles an ignimbrite typified by a fragmented texture comprising of a mixture of glass and fragments of rock crystals, less than 1mm in size. Some of the clasts display a pegmatitic texture with quartz and feldspar intergrowths (Plate 3.1.5).

The feldspars account for 3% and are up to 0.8mm in diameter. They are usually tabulate in shape, angular to subrounded and are mainly plagioclase. They vary from fresh to highly altered. Occasionally the grains are fractured. One example showed a small fracture and slight displacement in the twinning lamallae. Microcline feldspar is identified by the cross-hatched twinning. Very rarely the feldspars show micrographic texture intergrowth of quartz and alkali feldspar.

The matrix (c.21%) consists of clay minerals, dominantly kaolinite and chlorite, illite and sericite, derived by in situ alteration of unstable minerals and therefore not depositional. Consequently the clay-infill forms pockets between the grains (Plate 3.1.6) and sometimes appears squeezed between grains and distorted by compaction. Some of the grains do possess a very thin rim of clay coating the grains.

Because the grains are fairly densely packed and the matrix content is small, many of the grains are welded together. Dissolution occurs at the grain boundaries followed by precipitation of the silica. Meniscus fabric is evident at grain contacts distinguished by concavo-convex contacts where quartz has been precipitated, although some grain to grain contacts are sutured where there is a mutual styolitic interpenetration of grains resulting from compaction (Plate 3.1.3).

CL

A variety of rock fragments in the Mulloch Hill Conglomerate are exposed using CL, for example the violet CL colour of composite quartz, contrasting with bluish-purple colour of vein and igneous quartz (Plate 3.8.1 and 2). Under a normal petrographic microscope heavy minerals are too small to be identified, and were often overlooked, yet under CL a lot of yellow CL coloured apatite is present (Plate 3.8.3). Similarly, the amount of feldspar in the Mulloch Hill Conglomerate, determined by microscope point counts was underestimated. Even the smallest feldspar grains luminesced bright-green, blue and buff colours, indicating that feldspar content accounted for as much as 20%, varying significantly from the original point count estimate of less than 5% (Fig. 5.1). This high percentage of feldspar confirms the petrographic evidence that the sediment is both mineralogically and texturally immature.

Interpretation

As can be seen from the high matrix content, and the abundance and diversity of unstable rock particles, the sandstones are texturally and mineralogically immature. This indicates that they have not travelled far, because sorting of grain sizes is very poorly developed and the shapes of the clasts are dominantly elongate and angular. Futhermore there is no indication of recycling of clasts in the form of sharp corners on the grains.

The rock particles include schistose metamorphic rock, polycrystalline quartz, and igneous clasts of granite, dolerite, microdiorite, ignimbrite. These clasts may have been derived from supracrustal rather than plutonic source rocks with the quartz originating from pre-existing sediments, whilst the rock particles are fine-grained sediments, metamorphic, and effusive igneous rocks. Such a wide provenance is associated with a large drainage basin probably having a diverse bedrock lithology. The metamorphic mica schists are associated with low-grade metamorphism. Many of the basalts have been quickly quenched, consequently they possess a feathery rim. Furthermore, the vesicular arrangement of the plagioclase feldspars suggests that they crystallised in fairly deep water environments. The coarser-grained igneous rocks represent intrusive flows, possibly derived from dykes and sills, and the granites are associated with plutons. Thus it appears that coarse-grained intrusive rocks were being eroded as well as volcanics.

5.2.2 Mulloch Hill Formation

Lower Member

Section Nos: TW.19.146, TW.32.147

Type: Fine-grained lithic arenite

Localities: 19,32, Craighead

Description

The lower member of the Mulloch Hill Formation is characterised by fine-grained lithic arenites composed of quartz (c. 28%), lithic fragments (c. 20%), feldspar (20%), opaque minerals (c. 5%), and mica grains (c. 1%), embedded in a clay matrix. Texturally the sandstone resembles the sandstones in the middle of the Mulloch Hill Conglomerate (locality 1); compositionally however the former has fewer lithic fragments.

The quartz grains range in size from 0.02mm to 0.3mm diameter (coarse silt to medium sand grade) averaging approximately 0.1mm diameter (fine sand grade). They are generally of low sphericity, dominantly elongate although there are some tabulate-shaped grains. The quartz present is mostly monocrystalline, exhibiting both straight and undulose extinction, with occasional needle-shaped rutile crystals and vacuoles present, characteristic of plutonic quartz. Very rarely there are semi-composite quartz grains of igneous origin, and stretched metamorphic quartz characterised by elongated quartz crystals with smooth and crenulated borders.

The feldspar accounts for 20%. The crystals tend to be segregated by size and shape, not exceeding 0.8mm in diameter and more or less tabulate in shape. Plagioclase feldspar is dominant, distinguished by lamellar and Carlsberg twinning, whilst rarely microcline feldspar is present. Most of the feldspar shows varying degrees of alteration (mainly vacuolisation and sericitisation) causing a slightly mottled appearance.

Lithic fragments are sparsely distributed through the sediment and include metamorphic quartz schists, basic-intermediate igneous rocks, and siltstone clasts (Plate 3.2.1) which are similarly elongate to tabulate in shape and angular.

As with the underlying sediment the matrix (c. 25%) originates from the degradation of the constituent clasts and consists of clay minerals. Many of the grains possess a thin brown-coloured rim composed of iron oxide. The cement is dominated by quartz overgrowths, tending to be concentrated at grain boundaries (Plate 3.2.2).

Within the sandstones there is no evidence of grading. Apart from one large elongate structure measuring 1.2cm long by 0.1cm wide which is either a siltstone clast or burrow, the sandstones are generally lacking in structures. Throughout the Mulloch Hill Formation there are a number of brown-orange structureless blobs less than 0.1mm diameter which occur both singly and in groups. These are hydrated iron oxides (probably goethite), which are pseudomorphing after pyrite and are caused by the effects of weathering or groundwater on original or diagenetic pyrite.

At locality 32, the medium-grained poorly-sorted angular siltstones are composed mostly of monocrystalline quartz, with only rare polycrystalline quartz and feldspar, mica, opaque minerals and lithics, characteristically elongate to tabulate in shape. Calcite is patchily present, representing early calcite which has been re-suspended as detrital grains. Fine laminations can be picked out by subtle changes in colour. Disarticulated brachiopod valves and other fossil fragments are present (Plate 3.2.3).

<u>Middle Member</u>

Section Nos: TW.41.149, TW.41.150, TW.41.151

Type: Fine-grained lithic arenite

Locality: 41, Craighead

<u>Description</u>

As previously mentioned, the Middle Member of the Mulloch Hill Formation differs dramatically from both the underlying and overlying sediments. There are three main lithologies present at locality 41 1) a fine-grained poorly-sorted sandstone, 2) a medium- to fine-grained siltstone and 3) a mudstone. Each will be dealt with separately.

The pale red coloured fine-grained sandstone, TW.41.151, is composed of quartz, feldspar, lithic fragments and opaques cemented dominantly by calcite (Plate 3.2.4). Unfortunately, the fine grain-size inhibits calculation of percentages of the constituent minerals. Quartz is dominant, ranging in size from 0.125-0.2mm (fine sand grade), resulting in a moderately-sorted texture. Grains are fairly angular and of low sphericity;

they are elongate to subrounded in shape. Monocrystalline quartz is dominant, whilst feldspar and lithic fragments are rare. Because the grain packing is not tight there is very little authigenic quartz cement present, and the main cementing agent is calcite. There is a decrease in the quantity of clay matrix which accounts for less than 10%, which is composed generally of kaolinite and chlorite.

Neither grading nor laminations are evident within the sandstone. Fossil concentrations are composed of thin-shelled disarticulated brachiopod valves, a few solitary corals, and disarticulated crinoid ossicles. The brachiopod shells are composed of slightly wavy sub-parallel laminated calcite and parallel fibrous structures running sub parallel (slightly inclined) to the outer margin. Some valves display very thin haematitic rims, and occasionally have detrital quartz grains impregnating the outer wall.

A number of the valves were partially infilled with sediment, thus showing geopetals (Plate 3.2.5). The fabric consists of slightly finer-grained material, in places resembling mud clasts, up to 0.7cm in diameter. They are generally elongate in shape.

The mudstone is extremely fine-grained with detrital quartz grains less than 0.06mm in diameter (coarse silt grade). The contact between the mudstone and overlying sandstone is very sharp, with larger detrital quartz grains protruding into the mudstone (Plate 3.2.6). The mudstone has a greyish red colour, composed of an aggregate of calcite, quartz, clay material and less than 1% opaques. It is relatively well-sorted containing no sedimentary structures with neither organic material nor shell debris.

In the medium-grained sandstone there are a number of flasers and burrows present and the disturbed appearance is attributed to bioturbation. The fairly angular, elongate to tabulate shaped clasts do not exceed 0.4mm in diameter (medium sand grade). There are a number of irregularly shaped black flasers which are composed of finer clayy material, having jagged and frayed edges. Perhaps the most distinguishing characteristic is the presence and effects of bioturbation, and as a consequence the faint laminations are arched up. The structures have irregular shapes and are infilled by finer sediments.

Rarely there are some thin calcite veins, approximately 1mm wide, composed of sparry calcite.

Upper Member

Section Nos: TW.89.152, TW.89.153

Type: Fine-grained lithic arenite

Locality: 89, Rough Neuk

Description

The lithologies in the Rough Neuk Quarry representing the upper member of the Mulloch Hill Formation are characterised by moderately-sorted fine-grained sandstones

(Plate 3.2.7) and medium-grained siltstones composed dominantly of quartz (c. 30%), feldspar (c. 20%), very rarely lithic fragments (c. 10%), opaque minerals (c. 3%) and mica (less than 1%). There is no dramatic change in composition, only in the percentages of the constituents. Monocrystalline, quartz is abundant. The feldspars possess fairly poorly developed crystal outlines and are extensively altered by sericitisation, resulting in a mottled appearance. Remnants of multiple twinning are still apparent (Plate 3.2.8). Detrital clay matrix accounts for as much as 30%, infilling in pore spaces. The matrix is secondary, originating from the breakdown of the grains and has a fairly uneven distribution. Early stages of clay cementation are indicated by authigenic coatings of clays forming around the detrital grains, producing a brown rim inhibiting the growth of pore-filling quartz. Because it is rare to see inclusions trapped at the boundary between detrital and authigenic quartz, it is hard to determine the degree of authigenic quartz cementation. It can however be detected by the presence of euhedral terminations on some grains. Infrequently black styolitic seams are present, having a similar appearance to those seen at locality 41.

Small (less than 2mm diameter) oval to round shaped structures interpretated as burrows contain a number of angular, slightly finer-grained quartz grains of low sphericity, embedded in an opaque matrix. These may be attributed to burrows, but in general the rest of the lithology lacks the mottled appearance normally associated with bioturbation. Fossils are scattered throughout the siltstones and sandstones (Plate 3.2.9). The siltstones which when weathered have a blocky convex upper surface, are also poorly sorted but contain more calcium carbonate (c. 20%).

CL

Towards the top of Rough Neuk Quarry there is a gradual decrease in clay matrix, resulting in a much cleaner sediment. CL shows a diverse and abundant rock fragment assemblage in the bioclastic sandstones of the Mulloch Hill Formation (Plate 3.9.1 and 2). Feldspar is easily picked out, accounting for 20-30%, luminescing green, blue and buff colours similar to those in the underlying Mulloch Hill Conglomerate. Unlike quartz there is no evidence that feldspar CL is related to specific igneous or metamorphic sources, but the feldspar suite comprising of three different colours may indicate different sources. Some quartz grains are composite, possessing a bluey-purple luminescence colour. Apatite is also present and is noticeable by the yellow luminescence colour.

Carbonate cement is easily detected, accounting for up to 50%, in the Rough Neuk Sandstones, and occasionally small voids are filled with concentrations of lighter yellow-orange luminesce colours occupying the centre of the void, with darker-orange concentrations on the outer rim corresponding to ferroan and non-ferroan calcite (Plate

3.9.3). The calcite may have originally been derived from fossil fragments which were dissolved. Subsequently carbonate was precipitated in the voids. Therefore the voids must have been present prior to precipitation.

Many fossil fragments such as crinoids and gastropod fragments are present.

Interpretation

According to Folk's (1951) scale of textural maturity based on sorting and roundness, the Mulloch Hill Formation is texturally immature, in that at the base of the Formation there is relatively little clay matrix and the detrital grains are poorly sorted and not well rounded. Furthermore the sandstones are mineralogically immature containing minerals which are unstable, such as feldspar. Pettijohn (1975) points out that the survival of feldspar is related to the intensity of the decay process. He suggests that where there is high relief and rapid erosion the feldspar could escape decomposition whereas in low relief and retarded erosion the feldspar would be destroyed. Apart from the reduction in abundance and diversity of lithic rocks and feldspars there seems to be no change in the composition of the hinterland providing the detritus. The sharp corners of the grains suggest first-cycle sedimentation and the angularity and dominant elongate shape indicates that the sediments have undergone a short transportation history.

Most of the calcite cement is derived from the dissolution of the shell fragments. Pressure due to the weight of the overlying sediment has dissolved the points of contact between adjacent grains. At these points, the solubility of the calcium carbonate is increased and the material of the shell fragments goes into solution and is eventually re-deposited as crystalline calcite in any open spaces available. At locality 41, the abundance of calcite may be related to the abundance of fossil concentrations and to a shallower depth of deposition. Clearly there is an increase in fossil fragments from the base of the Mulloch Hill Formation to the top of Rough Neuk, reflecting gradual colonisation of the shelf area. The fossils include brachiopods, solitary corals, bryozoans and gastropods, indicative of shallow marine conditions.

5.2.3 Glenwells Shale Formation

Section No: TW.53.154

Type: Siltstone

Locality: 53, Craighead

Description

The laminations in the Glenwells Shale are defined by colour changes, grain-size differences and also by differences in clay content. The description below is from one specific thin-section typical of the petrographic characteristics of the lower member of the Glenwells Shale, and the laminations are described in ascending order.

The thickest (basal) lamina is up to 1.7cm thick composed of a yellow-grey coloured micritic mudstone (Plate 3.3.1). There are a number of poorly-sorted quartz grains ranging in size from 0.01 to 0.2mm diameter (silt to fine sand grade), generally less than 0.1mm in size. The tabulate to elongate shaped quartz grains are mainly monocrystalline, quartz exhibiting both straight and slightly undulose extinction and occasionally containing vacoules and inclusions. A few grains were composite with sutured boundaries characteristic of a metamorphic source. Some quartz is being actively dissolved by calcite.

The grains are found in a clay matrix which only accounts for less than 4%, and as a result the main cementing agent binds the sediment together. The cement is largely composed of micritic ferroan calcite. Where there are small cavities the calcite has been precipitated as medium-grained calcite crystals.

Opaque minerals are present (c. 5%), probably pyrite, and the sediment appears muddy due to the presence of thin (less than 0.1mm thick) black flasers; concentrations of clay rich material. There are a number of large solution seams present, over 2.6cm long and approximately 0.5mm wide (Plate 3.3.1). These low amplitude stylolites are composed of multiple seams of insoluble material such as clay, and pyrite, which give it a very dark appearance (Plate 3.3.2).

Throughout this lamination there are unidentifiable fossil fragments, as well as a few crinoid ossicles and thin walled, articulated and disarticulated ostracods (Plate 3.3.3 and 4). The ostracods are filled with silt and sparry calcite. Near the base the lithology appears slightly mottled possibly attributable to bioturbation (Plate 3.3.5 and 6).

The overlying light-grey fine-grained silt horizon is approximately 0.3cm thick. The boundary between it and the previous micritic siltstone is sharp. This moderately sorted siltstone consists of a medium- to coarse-grained aggregate of quartz-feldspar-opaques, cemented dominantly by quartz and set in a clay matrix. The detrital quartz grains are generally elongate to tabulate in shape and angular to subrounded, with the grain-size ranging from 0.01 to 0.02mm in diameter (medium silt grade). Monocrystalline quartz (c. 99%) is dominant. Feldspars are sparse, accounting for less than 1%, and are mainly sanidine, which has been subject to alteration.

The boundary with the succeeding coarse-grained dark-grey coloured siltstone (c. 0.1 and 0.05cm thick) is sharply gradational. As well as being finer-grained the siltstone is muddier, and slightly better sorted. There are only a few elongate, angular to subrounded monocrystalline quartz grains present. These tend to show a preferred orientation parallel to bedding. Feldspar is exceedingly hard to identify due to the small size of the crystals but their presence is almost negligible (less than 1%). The opaques, largely pyrite , contribute to the dark colouration and the matrix consists of clay material, probably kaolinite and illite, and the flakes also show a preferred orientation parallel to bedding.

Interpretation

Laminations in the Glenwells siltstones may be products of dilute turbidites, associated with Td-Te Bouma sequences. The better-sorted, lighter coloured laminae and finer-grained laminae are the products of the tails of the turbidites and these are regularly intercalated with darker coloured, fairly poorly-sorted, coarser-grained laminae representing the mud layers. Generally the decrease in grain size and dominance of quartz (occurring as the larger detrital grains) indicates that the sediments have travelled further from the source area. The Glenwells Siltstones may record sedimentation further out on the fan. The abundance of calcium carbonate may originate from the dissolution of shelly fragments which subsequently has been precipitated elsewhere. In the siltstones, the abundant fossil fragments including brachiopods, corals, crinoid ossicles and ostracods which again are associated with shallow marine waters.

5.2.4 Newlands Conglomerate

Section No: TW.55.156

Type: Pebbly, coarse-grained, lithic arenite

Locality: 55, Craighead

Description:

The Newlands Conglomerate is characterised by a very coarse-grained to medium-grained lithic arenite composed of quartz (c. 11%), lithic fragments (c. 59%), feldspar (less than c. 1%) bonded by a quartz cement and set in a clay matrix (Fig. 5.1 and 5.2).

Grain size spans 0.25 to 18.00mm in diameter, but more commonly is about 0.5mm (sand to gravel grade), with small pebbles up to 2.0cm in diameter. Quartz grains are generally of low sphericity, and tabulate to elongate shaped, varying from angular to subangular. Monocrystalline plutonic quartz is abundant (Plate 3.4.1) and polycrystalline sheared metamorphic quartz contains sutured boundaries between elongated crystals, whereas volcanic quartz crystal boundaries are fairly straight.

Alteration in the feldspars helps to distinguish the feldspar from the quartz. Feldspars are composed mainly of sandine, whilst plagioclase shows lamellae twinning. The grains are tabulate to elongate shaped, less than 0.6mm in diameter and subrounded.

The rock fragments present include elongate chert grains, a large felsic clast with granophyric quartz and possibly feldspar, rare clasts with altered volcanic textures and abundant small quartzitic clasts - some with obvious metamorphic foliation.

Matrix material accounts for less than 23% and is mostly kaolinite and illite, infilling the pockets between grains. Quartz overgrowths are quite prominent with euhedral crystal terminations and are selectively located near grain contacts. Most of the grains are coated with a thin brown rim of haematite and some are altered by chlorite and by calcite.

Compaction is reflected by concavo-convex contacts between grains, whilst deformation is indicated by the presence of fractures in the quartz grains (Plate 3.4.2).

CL

Confirming the point count results, CL shows that quartz is dominant, mainly of metamorphic origin, displaying a fairly uniform reddish colour, and is presumably from the same source as before (Plate 3.10.1 and 2). Composite and igneous quartz as well as low interdeterminal rock fragments were also present. Feldspars are scarce since most of them have been altered to sericite. Heavy minerals, namely yellow apatite are very rare. The fine clay matrix comprises authigenic kaolinite (blue CL). Some quartz pebbles up to 2cm in diameter contain very thin hair-like cracks. These pebbles have been fractured, and later annealed by quartz cement (Plate 3.10.3). Because these thin fractures can be traced into other grains, the episode of fracturing was post-depositional.

Interpretation

Poor sorting and angularity in the Newlands Conglomerate produces a texturally immature sediment. Thus it appears that the pebbles were not transported far from the source area. Furthermore, due to the fairly high content of unstable lithic fragments, the conglomerate is mineralogically submature as feldspars are very scarce. The lack of sorting, angularity of grains and lack of internal organisation imply minimal reworking. Increase in grain-size and re-introduction of lithic fragments may have been associated with the rejuvenation of the source area, namely uplift, allowing coarser material to be eroded. This source area was rich in quartz.

Seemingly, igneous rocks in the source area were not as abundant as in the Mulloch Hill Conglomerate.

5.2.5 Glenwells Burn Conglomerate 1

Slide No: TW.97.157

Type: Pebbly medium-grained, lithic arenite

Locality: 97, Craighead

Description:

The stratigraphically lowest part of the Glenwells Burn Conglomerate is medium-grained pebbly sandstone, has a distinctive green colour, and is composed of quartz (c. 13%), lithic fragments (c. 50%), feldspar (c. 1%), oxide minerals (c. 2%), and mica (c. 4%) (Fig. 5.1 and 5.2).

Grain-size ranges from 0.06 to 0.9mm in diameter (sand grade) averaging about 0.4mm(medium sand grade), and grains tend to be elongate to tabulate shaped and fairly angular (Plate 3.4.3). Quartz is dominantly of monocrystalline type: it is elongated to tabulate plutonic quartz, with a few smaller crystals of stretched metamorphic polycrystalline quartz. Feldspars are fairly scarce, accounting for less than 1%. The feldspar is mainly sanidine. Lamellar-twinned plagioclase and cross-hatch twinned microcline vary from fresh to altered, and are usually tabulate to rectangular in shape. Frequently, the feldspars display micro perithitic textures and myrmekitic textures (Plate 3.4.4).

Other rock fragments include basalt containing long laths of plagioclase (resembling a dolerite), small clasts of schistose metamorphic quartzite, occasionally foliated polycrystalline quartz and sediment clasts, a large (1.1mm in diameter) brown siltstone clast, and a fine-grained sandstone clast, composed dominantly of quartz.

Matrix is derived from the breakdown of the unstable components and tends to accumulate in pockets. The fairly high matrix content (23%) gives rise to a matrix-supported sediment.

Calcite occurs as a secondary cementing agent. In places it is seen replacing clasts such as quartz and feldspar. The cement is patchily developed, developing almost into a poikilitic texture. The calcite probably post-dates the quartz cement, infilling empty pores.

5.2.6 Glenwells Burn Conglomerate 2

Section No: TW.98.158

Type: Pebbly medium-grained, lithic arenite

Locality: 98, Craighead

Description:

The second Glenwells Burn sandstone is made up of quartz (c. 10%), lithic fragments (c. 33%), feldspar (less than 5%), opaque minerals (c. 8%) and mica (c. 6%) (Fig. 5.1 and 5.2) cemented dominantly by authigenic quartz overgrowths and embedded in a clay rich matrix (Plate 3.4.5).

Detrital grain sizes range from 0.02mm to 17.00mm (sand to gravel grade), averaging approximately 0.3mm (medium sand grade). Angular to subrounded quartz is dominant, commonly elongate to tabulate in shape. Monocrystalline quartz, characteristic of volcanic origin, is dominant with a few stretched metamorphic polycrystalline quartz crystals and a few semi-composite quartz fragments of possible vein origin.

Fresh to altered feldspars occur in very low numbers, usually sanidines with a few twinned plagioclase and microcline crystals of tabulate to rectangular shape, and the grains are slightly smaller than the quartz grains (less than 0.1mm).

The lithic fragments include highly altered clasts with vague indications of originally volcanic textures, some polycrystalline quartz with fairly sutured internal boundaries (Plate 3.4.6), and cherty microcrystalline quartz. Haematite is distributed unevenly throughout the sediments, coating some grains. Oxidation of opaque minerals gives rise to the general red colour.

The clay matrix (43%) (kaolinite, chlorite and sericite) originates from the in situ disintegration of the chemically unstable clasts. Some grains are actually seen partially broken down. Since the arenite is clast supported, few grains are in contact, thus siliceous cementation is dominated by quartz overgrowths, as indicated by fairly straight grain terminations and by concentrations of vacuoles near the outer wall. Calcite cementation is inconspicuous, occurring in voids and dissipated throughout, and rarely of crystalline form.

<u>CL</u>

The second Glenwells conglomerate contains a mixture of igneous and metamorphic quartz displaying brown and blue luminescence colours (Plate 3.11.1 and 2), whereas the feldspars are bright blue, green in CL colour and fresh. The rock fragment assemblage also includes: acid igneous rocks containing a lot of apatite, other altered igneous grains (including a lilac composite clast with abundant feldspars) and metamorphic reddish coloured grains with a platy appearance. Many clasts display thin fractures filled with orange-luminescing carbonate (Plate 3.11.3).

<u>Interpretation</u>

Both Glenwells Burn pebbly sandstones are texturally and mineralogically immature, composed of poorly-sorted, angular and elongated clasts. The clasts become gradually smaller, probably corresponding to a lowering of the source area. The composition of the pebbly conglomerates and pebbly sandstones are similar, although the greenish-coloured conglomerate has slightly more igneous, metamorphic and sedimentary rock particles. The conglomerates were also rapidly dumped, and do not appear to have travelled far, accounting for the lack of sorting.

5.2.7 Newlands Formation

Section No: TW.124 and 159, TW.124.160

Type: Fine-grained, lithic arenite

Locality: 124, Craighead

Description:

The Newlands Formation is characterised by bioclastic fine-grained sandstones verging on coarse-grained siltstones composed mainly of quartz (c. 23%), lithic fragments (15%), feldspar (c. 20%), opaque minerals (c. 20%) and mica (5%) occurring in a clay matrix and cemented by authigenic quartz (Plate 3.5.1 and 2).

The sandstones are poorly sorted with subangular quartz grains of low sphericity, their sizes ranging from 0.04 to 0.25mm diameter (silt to sand grade) though more commonly 0.1mm (very fine sand grade) diameter (Plate 3.5.3 and 4). Monocrystalline quartz exhibiting undulose and straight extinction is dominant whilst polycrystalline quartz is scarce. Most of the feldspar appears mottled due to alteration and crystals are occasionally replaced by calcite.

The matrix accounts for more than 15%, and is composed mostly of clay material and mafics, the oxidation of the latter produces the characteristic rusty-red pigmentation. This clay matrix is derived from the in situ breakdown of the detrital grains and is therefore secondary. Often it is difficult to recognise quartz overgrowths as distinct from original crystals because dust rims and crystal terminations are rare. Due to the poor exposure no sedimentary structures were observed but lack of structure is also reflected in thin sections, where none of the grains show preferred orientation, nor is there evidence of stratification or grading. Thin sections do exhibit a rather hazy mottled appearance, which may be attributed to bioturbation. Under close inspection the structures are irregularly shaped and infilled with much finer-grained material (Plate 3.5.5). In addition there are a number of dark brown coloured oval pockets c. 0.1cm diameter possessing an outer rim concentrated with slightly larger grains surrounding a finer-grained nucleus (Plate 3.5.6). Dispersed throughout the sandstones are fossil fragments including disarticulated brachiopod valves, ostracods and trilobite exuriaoappendages.

CL

Under CL, blue-luminescing feldspars account for 20-30% of the total composition, whilst apatite luminesces yellow (Plate 3.12.1 and 2).

Interpretation

Decreasing grain-size and the gradual reduction in lithic fragments reflects the hinterland being gradually eroded away. Correspondingly, the increase in clay content and reduction in unstable minerals indicates a slight increase in maturity. The sediments were probably dumped rapidly, resulting in poor sorting and angularity of the grains. The sub-stratum water interface was presumably oxygenated, and the sediments were subjected to post-depositional burrowing and bioturbation.

5.2.8 Glenshalloch Shale Formation

Middle Member

Section No: TW.129.162, TW.129.162

Name: Banded Shales

Locality: 129, Craighead

Description:

The basal shales are overlain by fine-grained laminated and banded fissile shales of the middle member of the Formation. The bands of laminations are defined by colour and grain-size differences (Plates 3.6.1 and 2). The light olive-grey coloured laminae are slightly coarser-grained, with quartz grains ranging in size from 0.01 to 0.09mm (silt to sand grade) and averaging 0.01mm (medium silt grade), producing a poorly sorted texture (Plate 3.6.3). The quartz content is high, dominantly composed of monocrystalline quartz, although one polycrystalline quartz (Plate 3.6.5) reaching up to 0.09mm in diameter was present. These are generally angular to subrounded and of low sphericity. Mafics are represented by diagenetic pyrite growing in layers. Within these bands there are brown organic flasers and in hand specimen fragments of graptolites are visible. The pale blue-green coloured bands are noticeably better sorted and are much finer-grained, with detrital quartz clasts varying in size from 0.02-0.04mm in diameter (clay to sand grade). Similarly, elongate to tabulate, angular, monocrystalline quartz is dominant. The clay matrix shows excellent orientation, increasing the fissility of the shale. These laminae tend to look cleaner and lack the brown organic streaks seen in the darker laminae, and graptolite fragments are absent. Infrequently occurring between the laminae, there are discontinuous laminae, thickening and thinning, composed entirely of closely-packed monocrystalline quartz (Plate 3.6.4). In some places they appear to be loading into the coarser bands (Plate 3.6.6), whereas sometimes they appear to form small rippled structures. Grading is demonstrated between the top of the darker laminae into the lighter laminae.

Upper Member

Section No: TW.131.163

Type: Very fine-grained quartz arenite

Locality: 131

Description:

Towards the top of the Glenshalloch Shale the shales are intercalated with thinly-bedded very fine-grained quartz-rich arenites (Plate 3.6.7). Detrital grains within the sandstones are moderately well-sorted, ranging from 0.04 to 0.8mm (sand grade), yet averaging around 0.1mm (very fine sand grade). Monocrystalline quartz is dominant, accounting for as much as 80-90% of the sediment. Characteristically, the grains are subangular to rounded and of low sphericity, elongate to tabulate in shape. There does appear to be a slight preferred orientation of monocrystalline quartz grains parallel to bedding and this is also reflected in the orientation of the mica (c. 5%) which occurs as thin flakes (Plate 3.6.8). Feldspars are rare (c. 1%) and are usually altered. The sandstones are fairly clean, with a matrix of less than 5%. In some instances quartz cementation is selectively located near grain contacts showing concavo-convex contacts, though sutured boundaries between the grains could be due to compaction rather than cementation.

Interpretation

The laminated shales in the Glenshalloch Shale represent typical thin-bedded turbidites, specifically Td-Te sequences. The light-green coloured well-sorted homogeneous shales are the products of dilute tails of high density turbidity currents, whereas the darker coloured laminae are poorly-sorted, coarser-grained and generally structureless, and they represent the mud layers. Anamously large clasts such as the rounded polycrystalline quartz grain were transported in the turbidity currents.

Despite their higher density and larger size, but because of their flakey shape, mica fragments tend to collect in finer sands and shales. Possibly the mica was derived from mica-bearing granites, and gneisses and mica-schists. Their abundance in the Glenshalloch Shale, combined with other sedimentological evidence, agrees with Lovell's (1969) observations that micas in turbidite sediments are more abundant in distal than proximal sections of the submarine fan. Also the preferred orientation of the clay minerals and mica flakes, and the lack of obvious burrow structures or disruption through bioturbation, accords with the previous observation made that fissility in shales is related to the absence of organic activity (Byers, 1974).

The high quartz content, good sorting and subrounded shape in the siltstone (in the upper member of the Glenshalloch Shale) indicates a higher degree of textural and mineralogical maturity. The quartz is largely monocrystalline. Polycrystalline quartz is less stable and may have been eliminated during a long transportation history (Blatt, 1967). Commonly quartz arenites are associated with a marked period of stability.

For sufficient time to produce these results the source area and site of deposition had to be tectonically stable, or the sand must have gone through several cycles of sedimentation. The former explanation is preferred, since there is no evidence of recycling in the quartz grains.

5.2.9 Upper Saugh Hill Grit Formation

Section No: TW.140.164

Type: Coarse-grained, lithic arenite

Locality: 140, Craighead

Description:

The base of the Upper Saugh Hill Grits, is represented by a pebbly sandstone - a combination of quartz (c. 9%), lithic fragments (c. 66%), (feldspar c.1%), and mica (9%) (Fig. 5.1 and 5.2) cemented by quartz and supported in a matrix of clay.

The larger equant clasts (up to 40mm) are moderately rounded, and of median to low sphericity, mostly tabulate in shape with a few slightly elongate grains. They are all composed of quartz: c. 67% polycrystalline stretched quartz, c. 29% monocrystalline, plutonic quartz and c. 4% sedimentary quartz (Plates 3.7.1 and 2). The monocrystalline quartz crystals exhibit both straight and undulose extinction and often have vacuoles concentrated into lines (Plate 3.7.3). Embayments are often seen along the outline of the grains where grains from the surrounding groundmass intrude in (Plate 3.7.4). The polycrystalline quartz exhibits both fairly straight and moderately sutured crystal boundaries composed of equant and non-equant sized composite crystals, characteristic of metamorphic origin. The rest of the groundmass is composed of detrital sand-grade debris, mostly of quartz, lithic fragments, volcanic clasts and possibly a few reworked clasts from below. These tend to be fairly poorly-sorted, ranging in size from 0.08 to 0.3mm (sand grade), averaging 0.2mm (sand grade), angular and of low sphericity.

Chemically unstable rock particles break down during diagenesis to produce the matrix of clay minerals, which accounts for 13%. Grains can be seen partially breaking down into matrix. The matrix tends to accumulate in pockets and sometimes appears squeezed and distorted, indicating compaction. The grains are cemented by authigenic quartz overgrowths and quartz cementation is concentrated at grain contacts.

Section No: TW.140.165

Type: Coarse-grained lithic arenite

Locality: 140, Craighead

Description:

The overlying sediments of the Upper Saugh Hill Grits are characterised by coarse-grained sandstones, finer-grained equivalents of the pebbly sandstone described above. Quartz accounts for (c. 20%) lithic fragments (46%), whilst feldspar (c. <1%), oxides (c. 1%), and mica (c. 10%) are minor constituents (Plate 3.7.5).

Quartz fragments are tabulate to elongate in shape and angular to subangular. Most quartz is monocrystalline and only a little semicomposite vein quartz is present. The smallest grains are up to 0.04mm and the largest 0.8mm, with a general median of 0.5mm (coarse sand grade) (Plate 3.7.6).

Feldspars only account for 1%, and vary from fresh to altered. Crystal habit is tabulate to rectangulate and the crystals are slightly smaller than the quartz (0.3mm), composed mostly of sanadine with a few lamellar-twinned plagioclase.

Other constituents include reworked elongate siltstone, and chert clasts. Matrix (c. 20%) is composed of broken down unstable clay minerals accumulating in pockets between the grains. Grain to grain contacts demonstrate the processes of pressure solution.

CL

Quartz is abundant in the Upper Saugh Hill Grits, mostly composed of metamorphic quartz with a few igneous quartz grains. Feldspar and apatite occur in small amounts, the former tending to be altered into kaolinite and as a result kaolinite is fairly abundant (Plate 3.13.1 and 2).

Interpretation

The wide spectrum of grain sizes displayed in the pebbly sandstone is due primarily to poor selective sorting. For grains to be rounded the sand grains need to have been abraded for a very long time and subjected to very high energy environment. However, the coarser grains of quartz appear slightly rounder because coarser grains tend to round more easily than fine ones, since they collide more vigorously and they are not cushioned by a water film. There are no abnormal relations between size and rounding thus eliminating the possibility of multiple source areas.

The dominance of quartz in the pebbly sandstones represents the winnowing out of a large volume of igneous and metamorphic rocks, whilst the micas suggest that the sediments were deposited in the distal sections of the submarine fan.

As in the clast composition of the pebbly sandstones (Chapter 4), there are noticeably fewer igneous rock fragments in the Upper Saugh Hill Grits compared with the stratigraphically lower Mulloch Hill Conglomerates and Glenwells Burn Conglomerates (Fig. 5.3). The gradual change in the composition of the Conglomerates through time, from a diverse rock fragment assemblage in the Mulloch Hill

Conglomerate to a metaquartz-rich pebbly sandstone in the Upper Saugh Hill Grits, appears to record the proximal unroofing of a metaquartzite basement which had a discontinuous cover of non-metamorphosed volcanic, low-grade metamorphic and sedimentary lithologies.

Plates 3.1 - 3.13 (Chapter 5)

Plate 3.1

MULLOCH HILL CONGLOMERATE FORMATION

Figure

1. Very poorly sorted, grain-supported lithic arenite. The rock fragments are set in a matrix of clay. Clasts are of low sphericity and are angular.
   TW.13.141. Scale: bar represents 1 mm, *PPL*.

2. Under crossed nicols the same section shows a diverse assemblage of rock fragments including monocrystalline and polycrystalline quartz. The large grain in the foreground is a volcanic rock, containing large laths of plagioclase set in a very finely crystalline matrix.
   Scale: bar represents 1 mm, *XPL*.

3. Monocrystalline quartz exhibiting straight and undulose extinction, and polycrystalline quartz, are abundant. Two types of grain-to-grain contact are evident 1) concavo-convex contacts and 2) gently sutured contacts.
   TW.13.142. Scale: bar represents 1 mm, *XPL*.

4. A very poorly sorted, very coarse-grained lithic arenite. The very large siltstone clast contains a number of fine veins, which have been infilled by quartz. The quartz crystals tend to increase in size from the fracture walls to the centre.
   TW.13.143. Scale: bar represents 1 mm, *XPL*.

5. The large grain in the centre field of view displays a pegmititic texture where there are quartz and feldspar overgrowths.
   TW.13.144. Scale: bar represents 1 mm, *XPL*.

6. The matrix of the lithic arenites is composed of clay, in particular kaolinite derived from the in situ alteration of unstable minerals. As a result, the clay frequently infills pockets in between the grains.
   TW.13.145. Scale: bar represents 1 mm, *XPL*.

PLATE 3.1

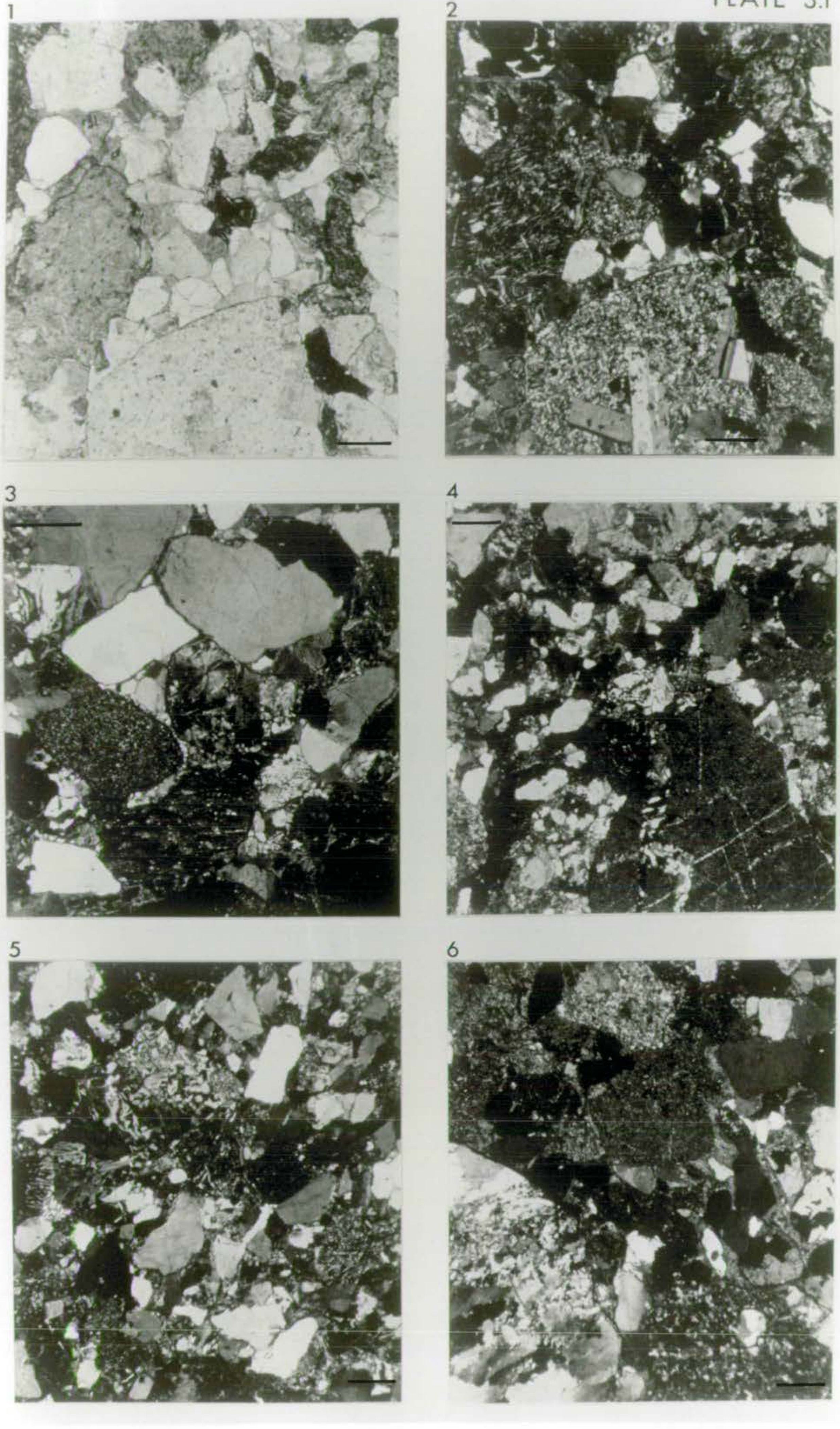


Plate 3.2

MULLOCH HILL FORMATION

Figure

Lower Member

1. Fine-grained lithic arenite embedded in a clay matrix. The slightly mottled appearance of the feldspars is attributed to alteration. The large grain in the centre of the field of view is a very fine-grained siltstone clast.
   TW.19.146. Scale: bar represents 1 mm, *XPL*.

2. Poorly-sorted, fine-grained lithic arenite. Quartz overgrowths tend to be concentrated at grain contacts, which are either concavo-convex or gently sutured.
   TW.32.147. Scale: bar represents 0.5 mm, *XPL*.

3. Cross-section of a gastropod, infilled with fine-grained sediment.
   TW.44.148. Scale: bar represents 1 mm, *XPL*.

Middle Member

4. Calcareous-cemented, poorly-sorted lithic arenite. Fairly large calcite crystals are characterised by the speckled appearance and twinning. The thin black organic-rich laminae is a stylolite.
   TW.41.149. Scale: bar represents 1 mm, *XPL*.

5. Disarticulated brachiopod valve, infilled with darker, finer grained mud. The valve is composed of slightly wavy, subparallel laminated calcite.
   TW.41.150. Scale: bar represents 1 mm, *XPL*.

6. Very fine mudstone overlain by a medium-grained, calcareous-cemented sandstone. Note the sharp contact.
   TW.41.151. Scale: bar represents 1 mm, *XPL*.

Upper Member

7. Moderately-sorted fine-grained sandstone. The small crystal in the centre left composed of long laths of plagioclase feldspar is
   TW.89.152. Scale: bar represents 0.5 mm, *XPL*.

8. Calcareous-cemented coarse-grained siltstone. Calcium carbonate is patchily distributed, often precipitated in small voids.
   TW.89.153. Scale: bar represents 0.5 mm, *XPL*.

9. Bioclastic coarse-grained siltstone. The fragment in the bottom left-hand corner is part of a crinoid.
   TW.89.153. Scale: bar represents 1 mm, *XPL*.

PLATE 3.2

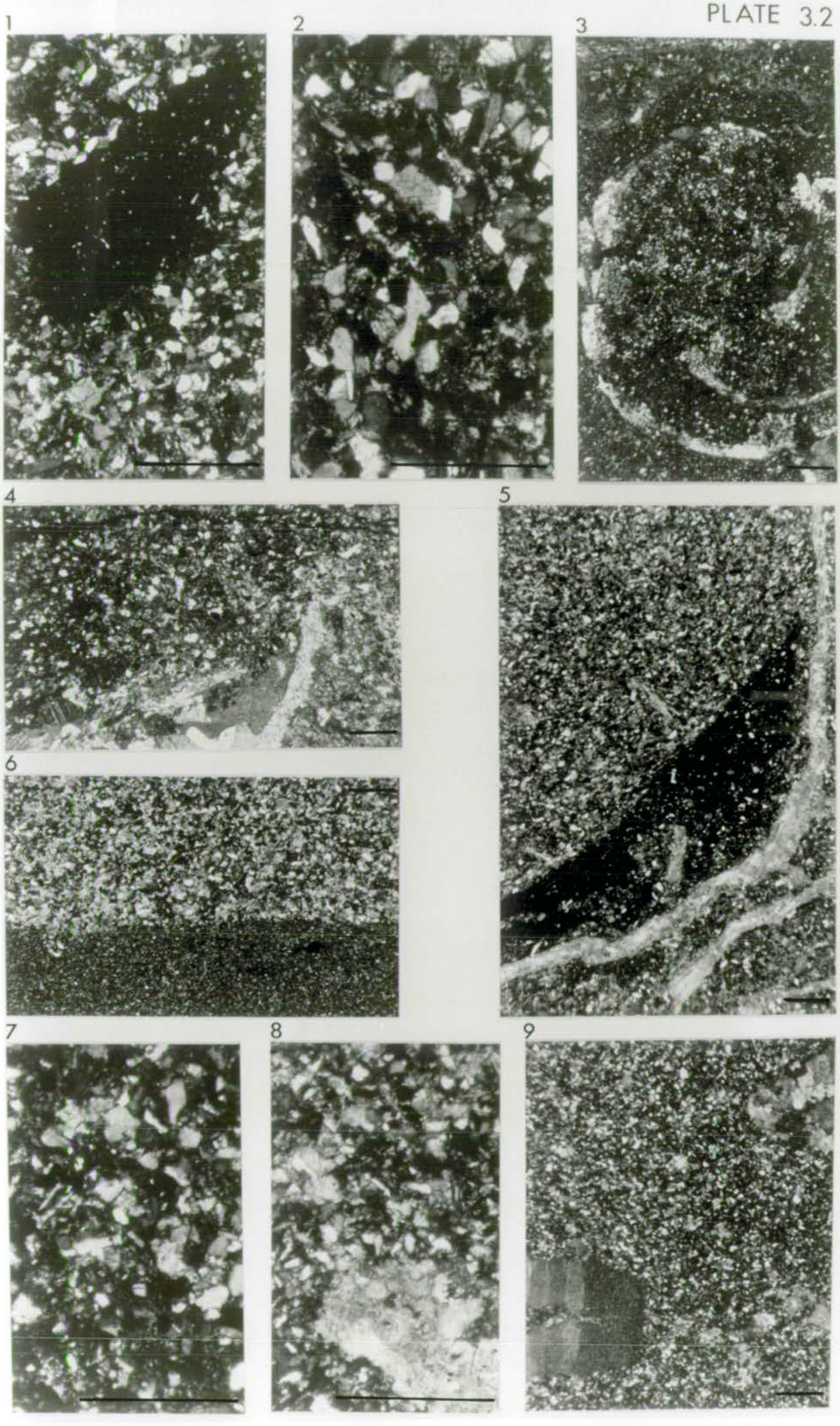


Plate 3.3

GLENWELLS SHALE FORMATION

Figure

1. Large black stylolite composed of multiple seams of insoluble material, occurring in medium-grained siltstone. The end part of the stylolite is frayed, resembling a horse-tail.
   TW.53.154. Scale: bar represents 1 mm, *XPL*.

2. Close up of the stylolite. The outer wall is slightly thicker and is broken into segments. Within these walls there are a number of coarser-grained detrital clasts. The circular object is a crinoid ossicle.
   TW.53.154. Scale: bar represents 1 mm, *XPL*.

3. Laminations in the siltstone are defined by variations in colour and grain-size. An apparently articulated ostracod occurs, just centre of view.
   TW.53.154. Scale: bar represents 1 mm, *XPL*.

4. Close up of the ostracod, which is infilled with calcite.
   TW.53.154. Scale: bar represents 1 mm, *XPL*.

5. The oval-shaped, lighter-coloured and slightly finer-grained areas represent burrows.
   TW.53.154. Scale: bar represents 1 mm, *XPL*.

6. Burrows found in the Tralorg Formation, from Penwhapple Burn.
   TW.P.155. Scale: bar represents 1 mm, *XPL*.

PLATE 3.3

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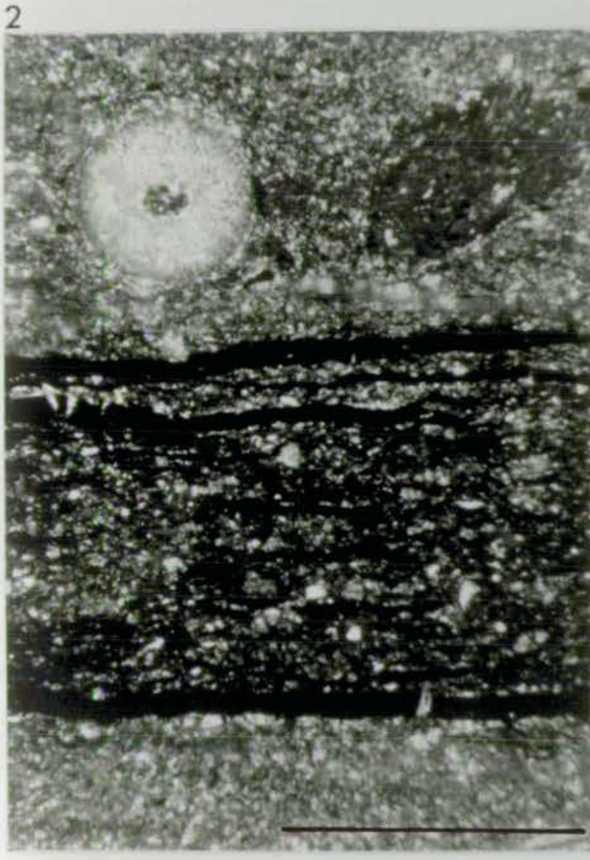
4

2



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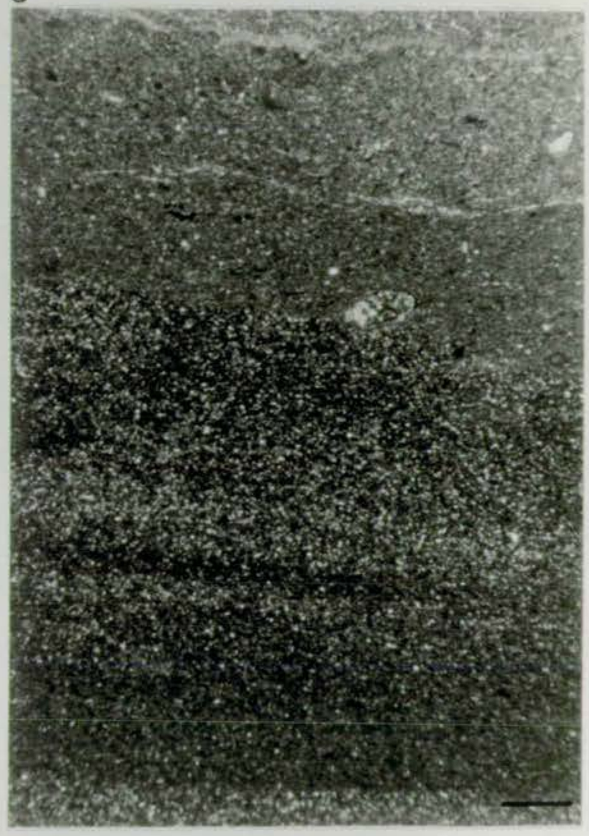

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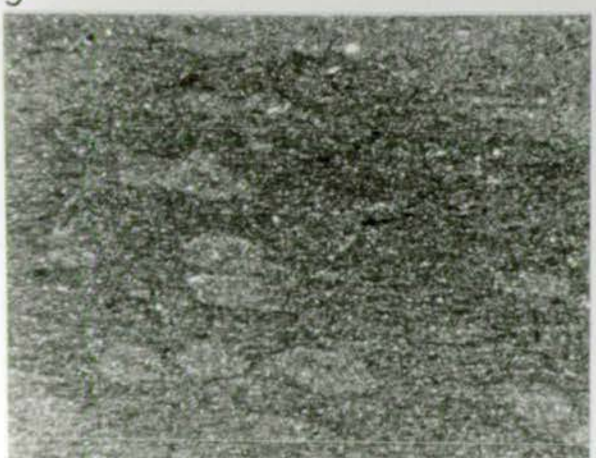

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Plate 3.4

NEWLANDS CONGLOMERATE

Figure

1. Very coarse-grained lithic arenite, bonded by a quartz cement and set in a clay matrix. Monocrystalline quartz is dominant. TW.55.156. Scale: bar represents 1 mm, *XPL*.

2. Compaction reflected by concavo-convexo contacts as well as gently sutured grain contacts. Approximately in the centre of the field of view a clast displays a granophyric texture. TW.55.156. Scale: bar represents 1 mm, *XPL*.

GLENWELLS BURN CONGLOMERATE 1

3. Poorly-sorted medium-grained lithic arenite. Lamallar-twinned plagioclase is differentiated from microcline feldspar as the latter exhibits cross-hatch twinning.
TW.97.157. Scale: bar represents 1 mm, *XPL*.

4. Medium-grained lithic arenite, contains a similar clast with a granophyric texture.
TW.97.157. Scale: bar represents 1 mm, *XPL*.

GLENWELLS BURN CONGLOMERATE 2

5. Very poorly-sorted, medium-grained lithic arenite. The large composite grain at the base is a fine-grained poorly-sorted sandstone.
TW.98.158. Scale: bar represents 1 mm, *XPL*.

6. Pockets between grains are infilled with clay matrix, mostly composed of kaolinite. Some of the quartz grains contain small inclusions. Although microcrystalline quartz is dominant there is some sheared polycrystalline quartz.
TW.98.158. Scale: bar represents 1 mm, *XPL*.

PLATE 3.4

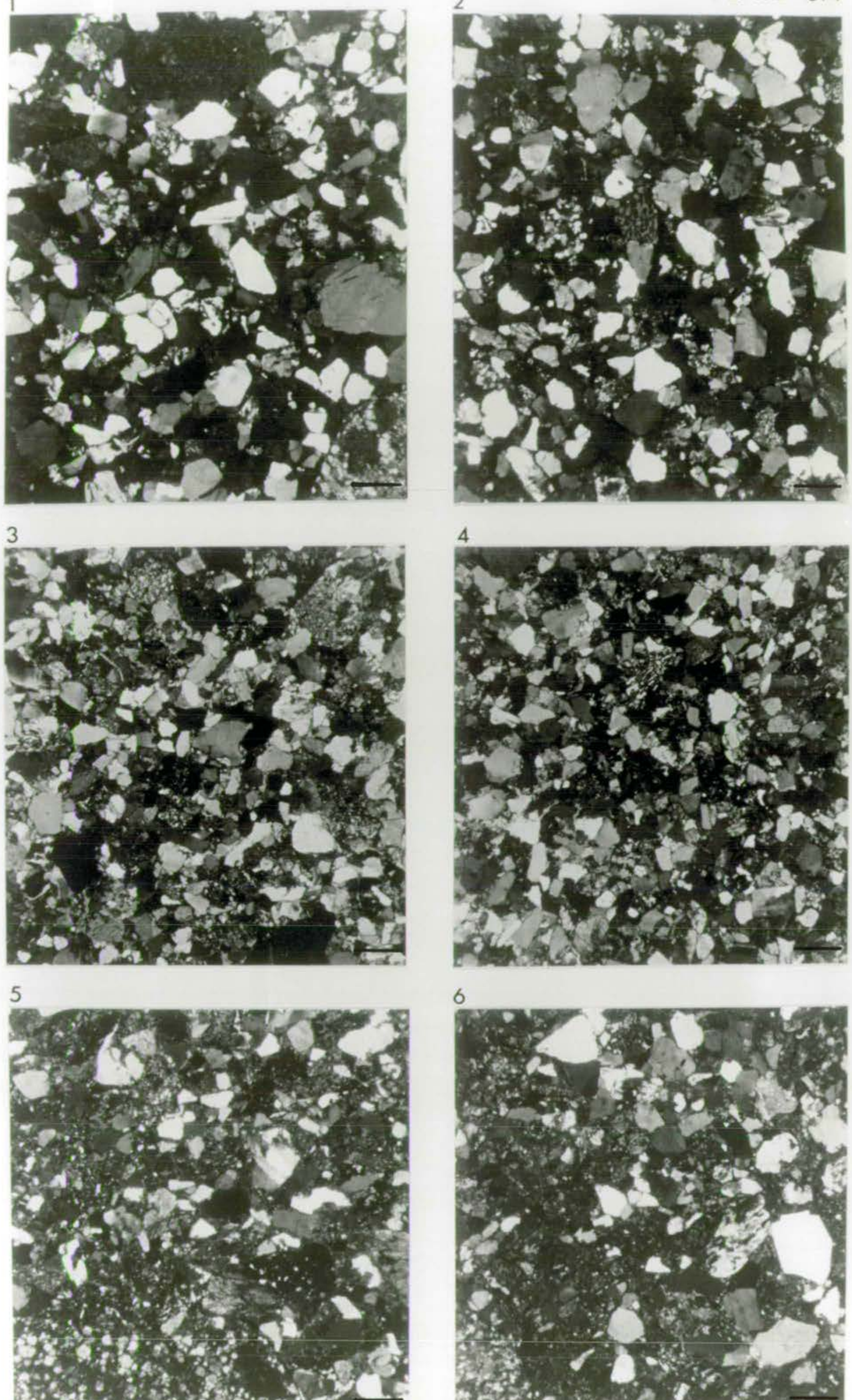


Plate 3.5

NEWLANDS FORMATION

Figure

1. Bioclastic coarse-grained siltstone. The slide shows the cross-section of a trilobite (top) and part of a brachiopod valve (left).
   TW.124.159. Scale: bar represents 1 mm, *PPL*.

2. Close-up of another trilobite fragment (centre). The sandstone is poorly sorted and the majority of the coarser grains are composed of monocrystalline quartz.
   TW.124.159. Scale: bar represents 1 mm, *XPL*.

3. Poorly-sorted coarse-grained siltstone. The large detrital clast is composed of monocrystalline quartz.
   TW.124.159. Scale: bar represents 1 mm, *XPL*.

4. Close-up of the poorly-sorted, coarse-grained sandstone.
   TW.124.159. Scale: bar represents 0.5 mm, *XPL*.

5. The general mottled appearance of the sediment is due to the presence of burrows. The oval burrows are infilled with finer-grained, darker-coloured material.
   TW.124.160. Scale: bar represents 1 mm, *XPL*.

6. Close-up of one of the burrows displaying an outer rim, which is concentrated with slightly larger grains.
   TW.124.160. Scale: bar represents 1 mm, *XPL*.

PLATE 3.5

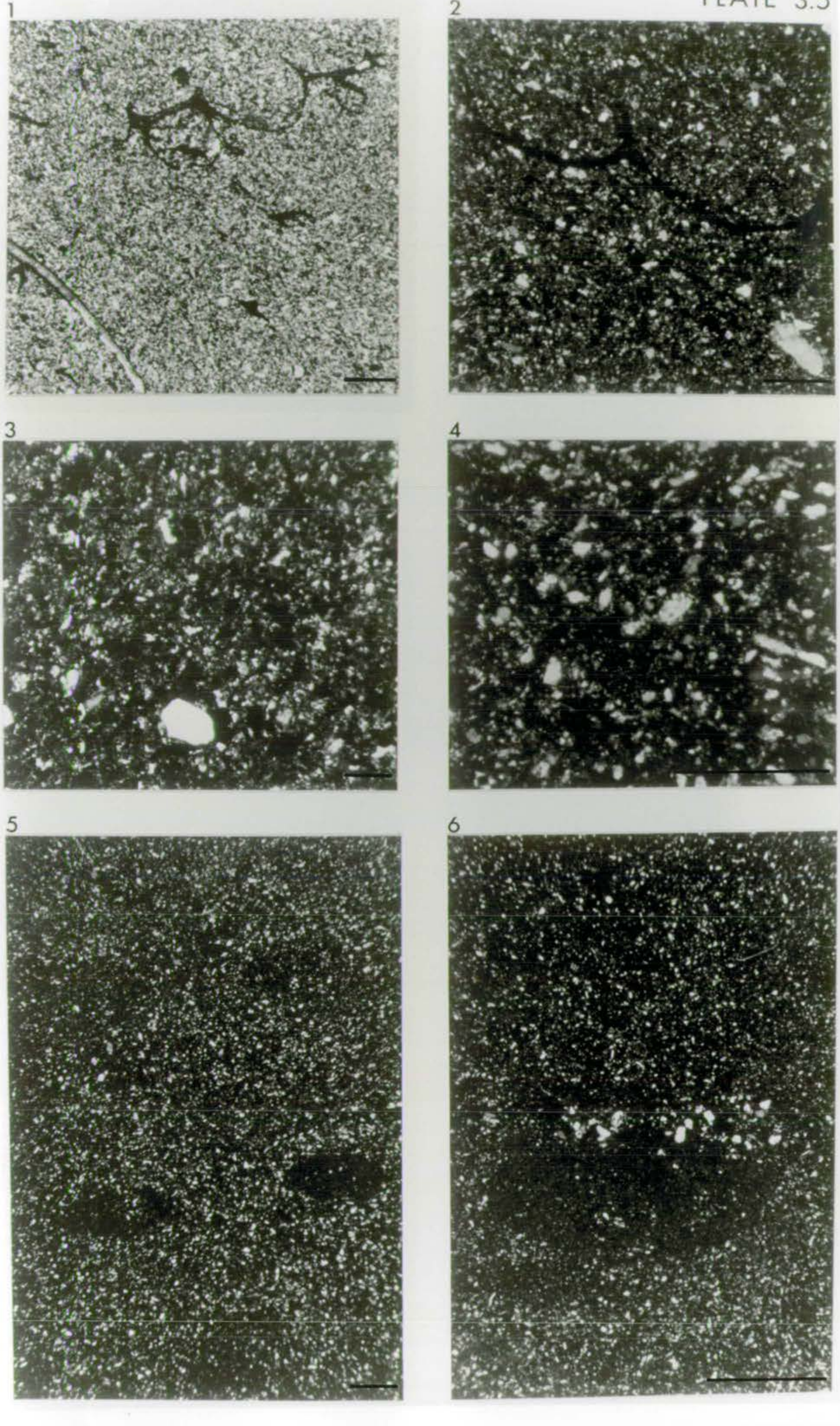


Plate 3.6

GLENSHALLOCH SHALE FORMATION

Figure

1. Laminated shale. Laminations defined by variations in colour, grain-size and organic content.
TW.129.161. Scale: bar represents 1 mm, *PPL*.

2. Right-hand view of the same section, under crossed polars. The darker laminae are coarser-grained, less well sorted and contain organic debris. Furthermore, the bases of the dark laminae are gradational, whereas the tops are sharp.
TW.129.161. Scale: bar represents 1 mm.

3. Close-up of the junction between the underlying lighter coloured laminae and darker laminae. The junction is gradational.
TW.129.161. Scale: bar represents 0.5 mm, *XPL*.

4. Laminated shale. Infrequently occurring between the laminae are discontinuous laminae, thickening and thinning, composed entirely of closely-packed monocrystalline quartz.
TW.129.162. Scale: bar represents 1 mm, *XPL*.

5. Close-up of the darker laminae, containing an anomalously large schistose quartz grain. The small flakes are composed of mica, probably muscovite.
TW.129.161. Scale: bar represents 0.5 mm, *XPL*.

6. Close-up of small-scale load structures, where the lighter coloured laminae is loading into the coarser, darker laminae.
TW.129.163. Scale: bar represents 0.5 mm, *XPL*.

7. Very fine-grained quartz arenite. Grains are moderately sorted.
TW.131.163. Scale: bar represents 1 mm, *PPL*.

8. The mica flakes within the quartz arenite appear to show a preferred orientation.
TW.131.163. Scale: bar represents 0.5 mm, *XPL*.

PLATE 3.6

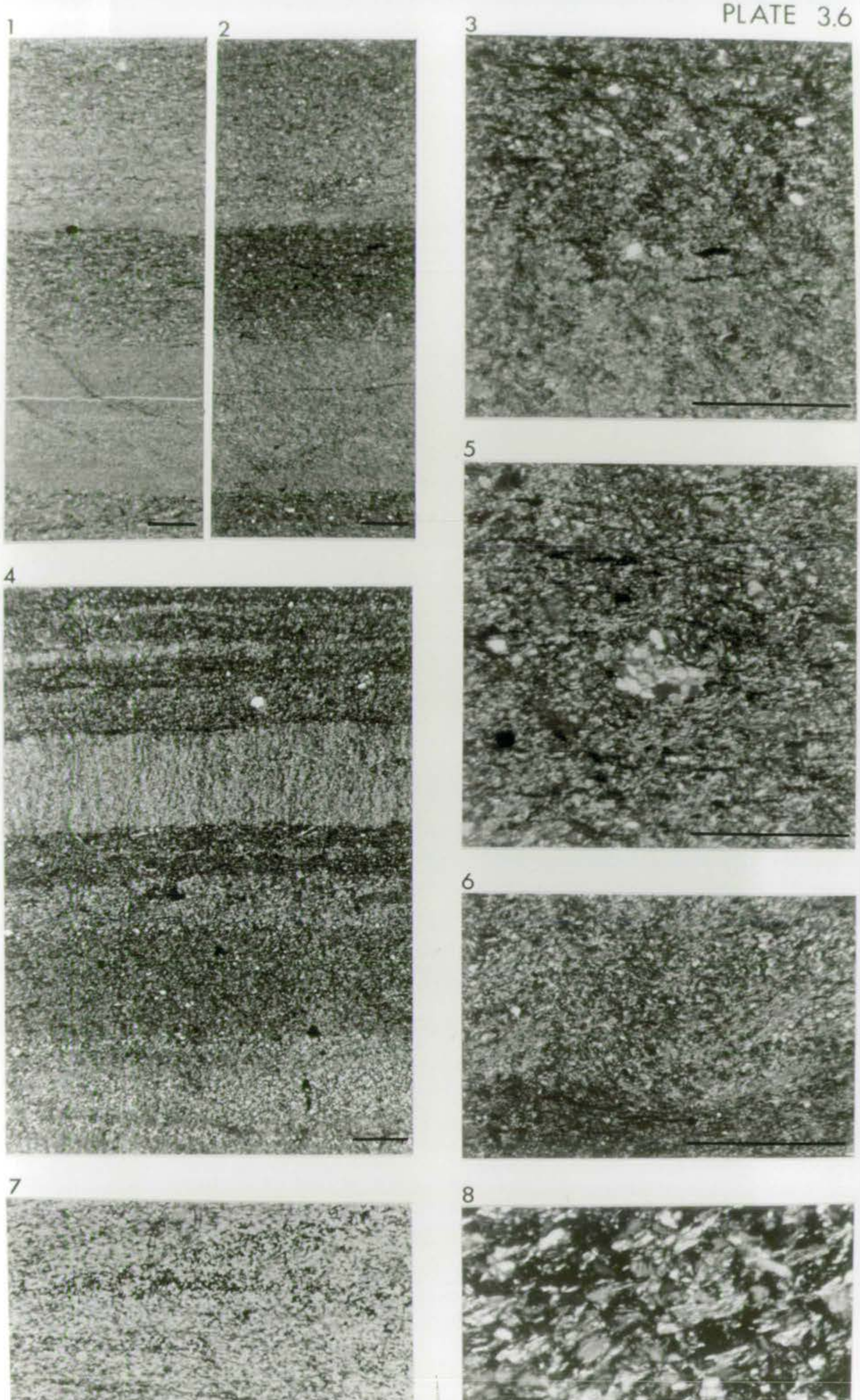


Plate 3.7

UPPER SAUGH HILL GRIT FORMATION

Figure

1. Coarse-grained, granular lithic arenite. The larger equant clasts are composed of polycrystalline stretched quartz (left) and monocrystalline quartz (right).
   The polycrystalline quartz exhibits both fairly straight and moderately sutured crystal boundaries, composed of equant and non-equant sized composite crystals.
   TW.140.164. Scale: bar represents 1 mm, *XPL*.

2. Poorly-sorted, granular lithic arenite. Chemically unstable rock particles are occasionally seen, partially breaking down to form the matrix. Quartz cementation is concentrated at grain contacts.
   TW.140.164. Scale: bar represents 1 mm, *XPL*.

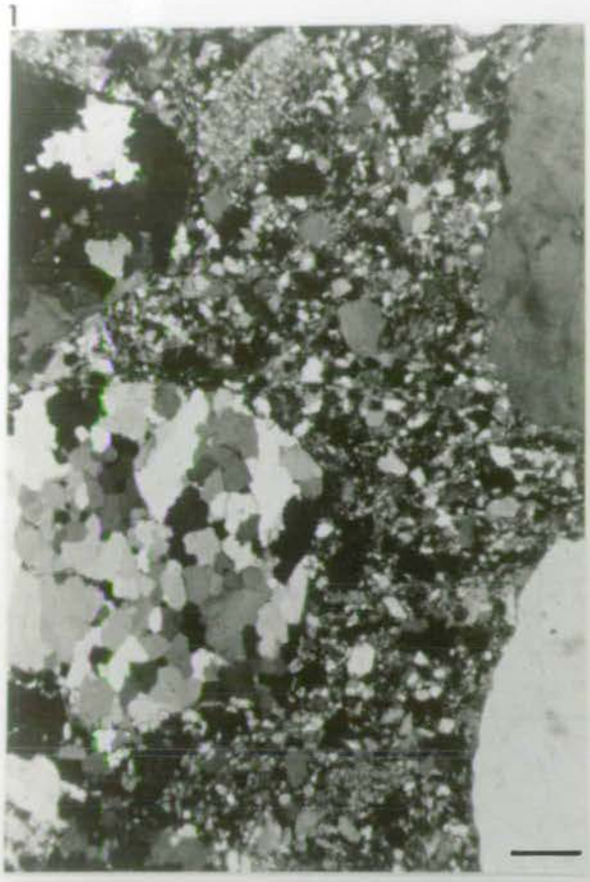
3. Close-up of a large monocrystalline quartz grain, containing dark vacuoles, and a needle-shaped inclusion. Embayments are seen along the outline of the grain, where grains from the surrounding groundmass protrude in.
   TW.140.164. Scale: bar represents 0.5 mm, *XPL*.

4. Two fairly large inclusions, occurring in a semi-composite and monocrystalline quartz (left).
   TW.140.164. Scale: bar represents 0.5 mm, *XPL*.

5. Coarse-grained lithic arenite, composed of detrital sand-grade debris, mostly of quartz and a few lithic fragments, and volcanic clasts.
   TW.140.165. Scale: bar represents 1 mm, *XPL*.

6. Poorly-sorted coarse-grained lithic arenite. The grains are elongate to tabulate shaped and are fairly angular.
   TW.140.165. Scale: bar represents 1 mm, *XPL*.

1



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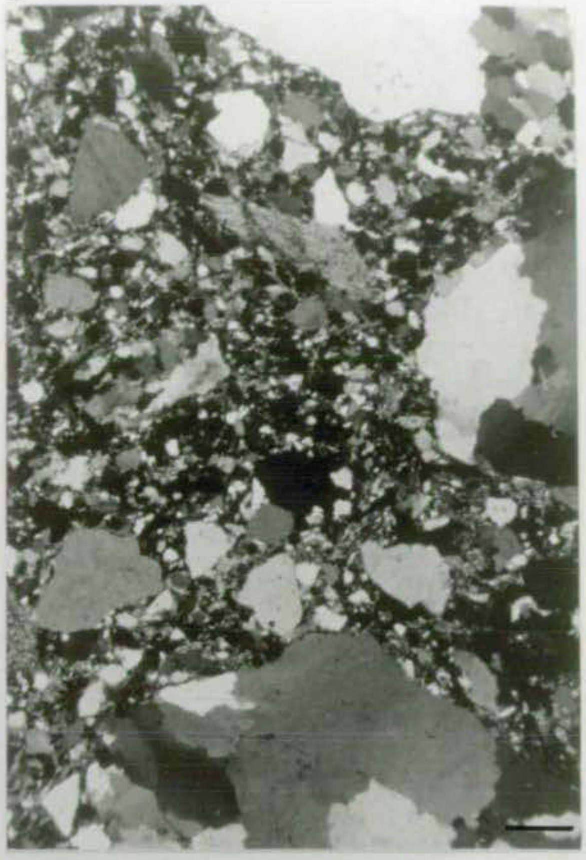

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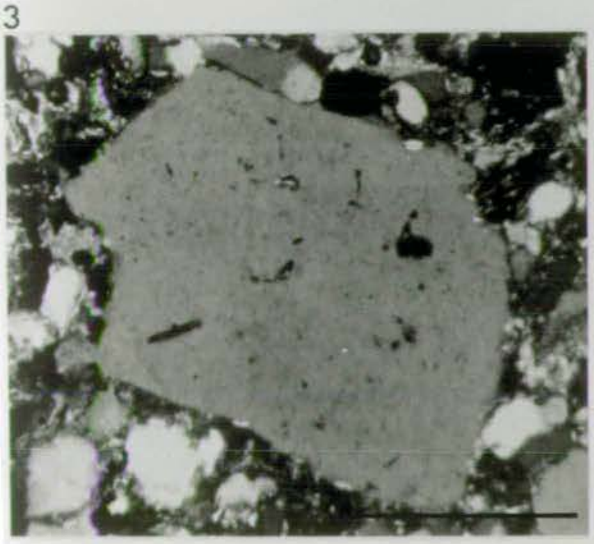

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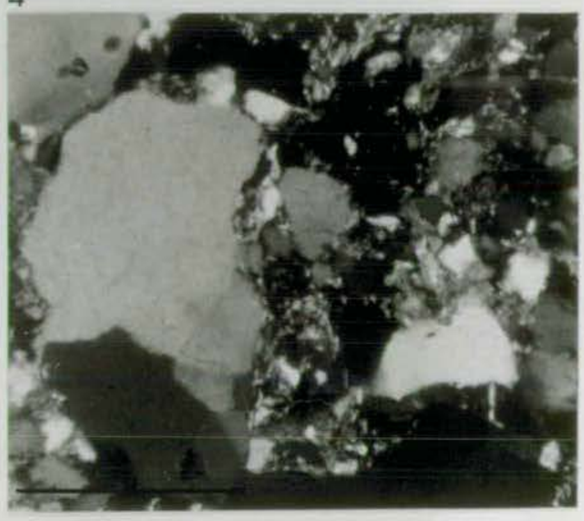

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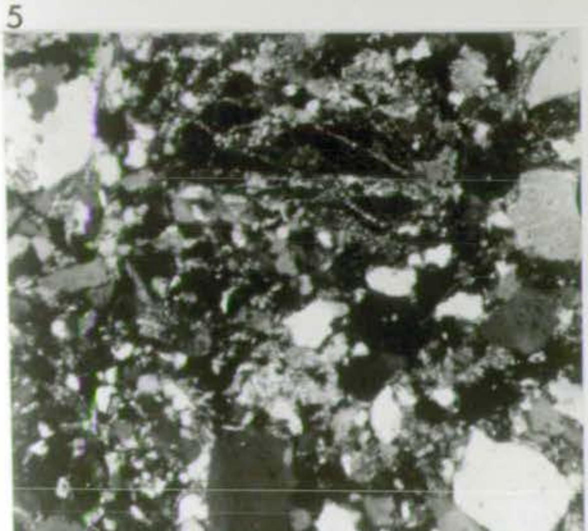

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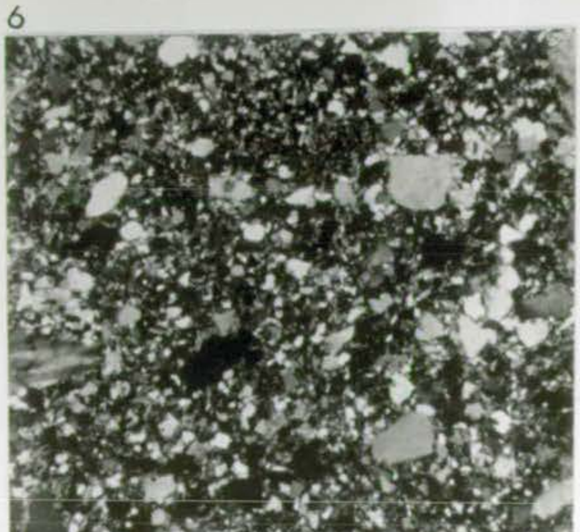


Plate 3.8

MULLOCH HILL CONGLOMERATE FORMATION

Figure

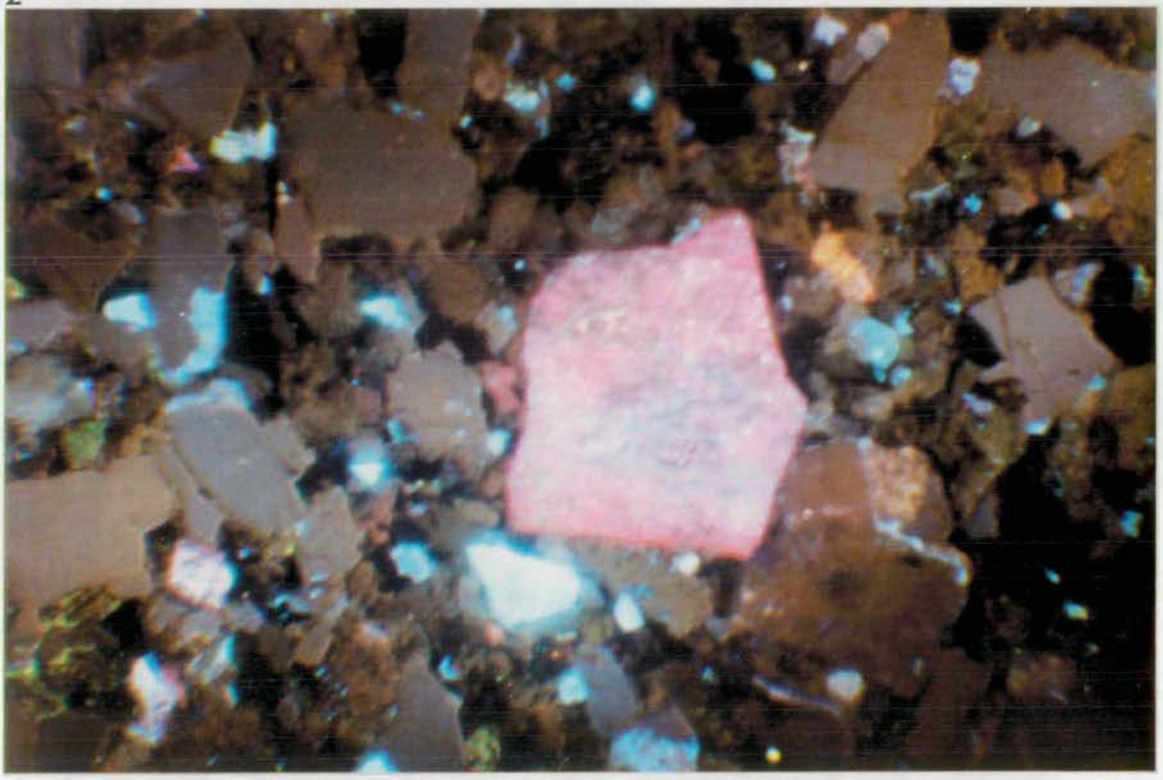
1. Poorly-sorted very coarse-grained lithic arenite.
   TW.13.185. Scale: bar represents 1 mm, *Tr.L.*

2. The lithic arenite contains both purple- and brown-luminescing quartz, whilst plagioclase feldspar luminesces a pale blue colour (over-exposed to white). The large grain in the centre right, luminescing pale pink, is a rock fragment, possibly of igneous origin, which would require probe analysis to determine its composition. Many other grains show their composite nature, and thus lithoclastic character, under CL.
   TW.13.185. Scale: bar represents 1 mm, *CL.*

3. Poorly-sorted, very coarse-grained lithic arenite. Apart from uniformly luminescing purple-grey quartz grains, many grains are revealed as composite under CL - possibly igneous clasts. Generally the feldspars luminesce a pale blue colour. Accessory minerals are composed of green-luminescing apatite.
   TW.13.185. Scale: bar represents 1 mm, *CL.*

1

2



1mm

3

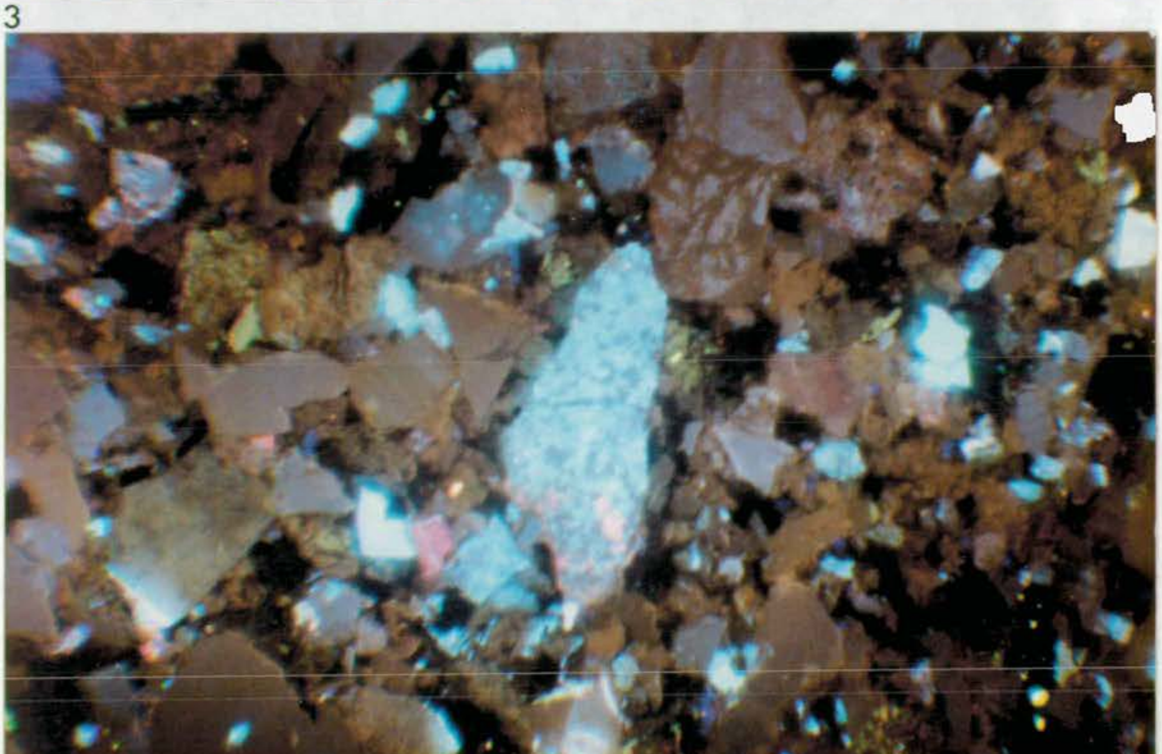


Plate 3.9

MULLOCH HILL FORMATION

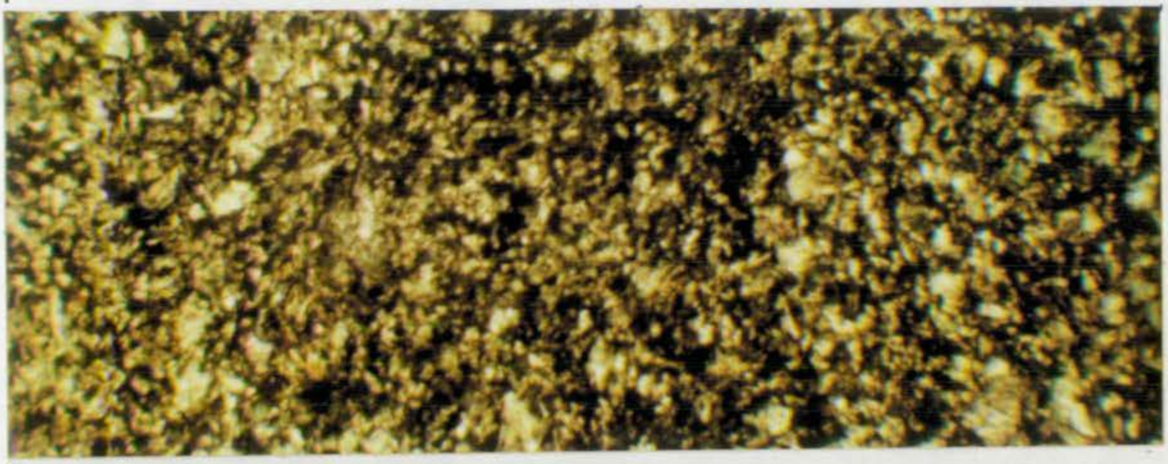
Figure

1. Moderately-sorted fine-grained sandstone.
TW.89.186. Scale: bar represents 1 mm, *Tr.L.*

2. Under CL, feldspars are easily distinguished luminescing blue and accounting for as much as 20-30% of the total volume. Furthermore, calcite cement is abundant (~50%) luminescing yellow-orange. In the centre of the field the oval shape composed of calcite is a cement-filled mould of a fossil, possibly a gastropod.
TW.89.186. Scale: bar represents 1 mm, *CL.*

3. A punctate brachiopod shell is revealed by CL in the centre of field. Adjacent small voids infilled with calcite exhibiting two different luminescing colours; a lighter yellow-orange colour in the centre surrounded by a darker orange rim, indicating two phases of calcite cementation. The calcite may have been derived by the dissolution of fossil fragments. Feldspars luminesce blue.
TW.89.186. Scale: bar represents 1 mm, *CL.*

1



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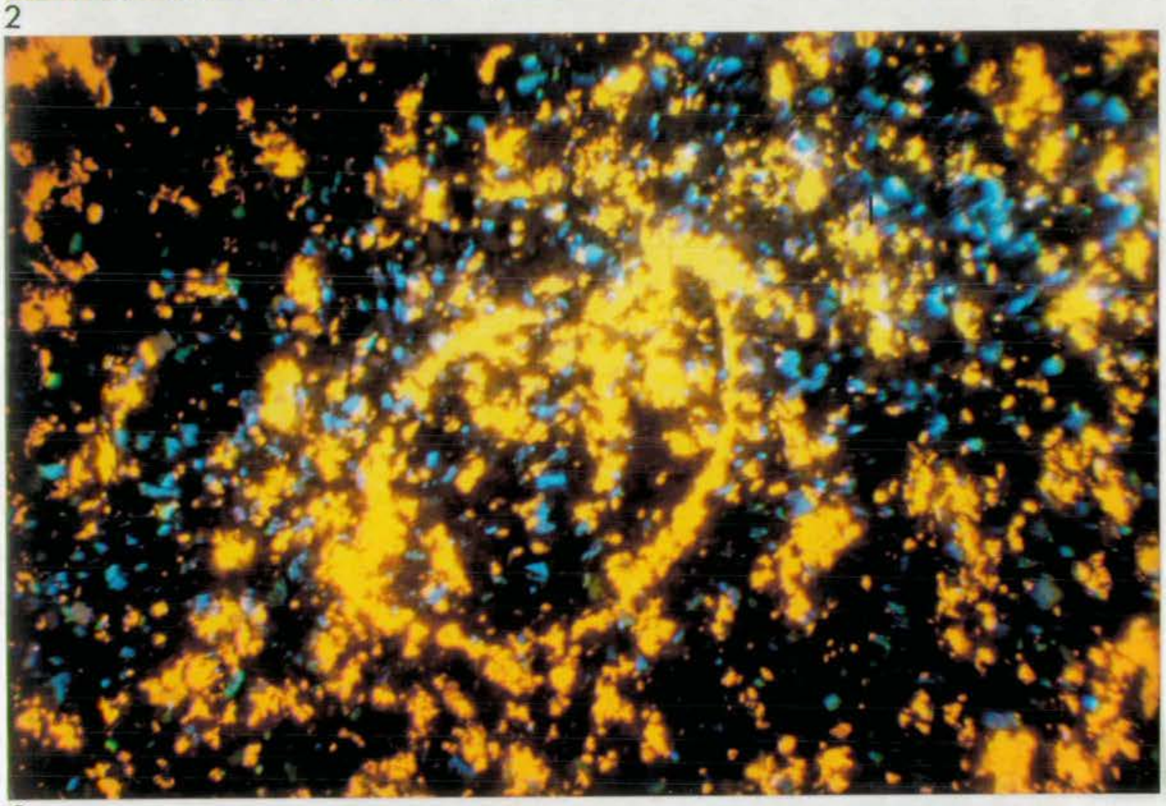


1mm

3

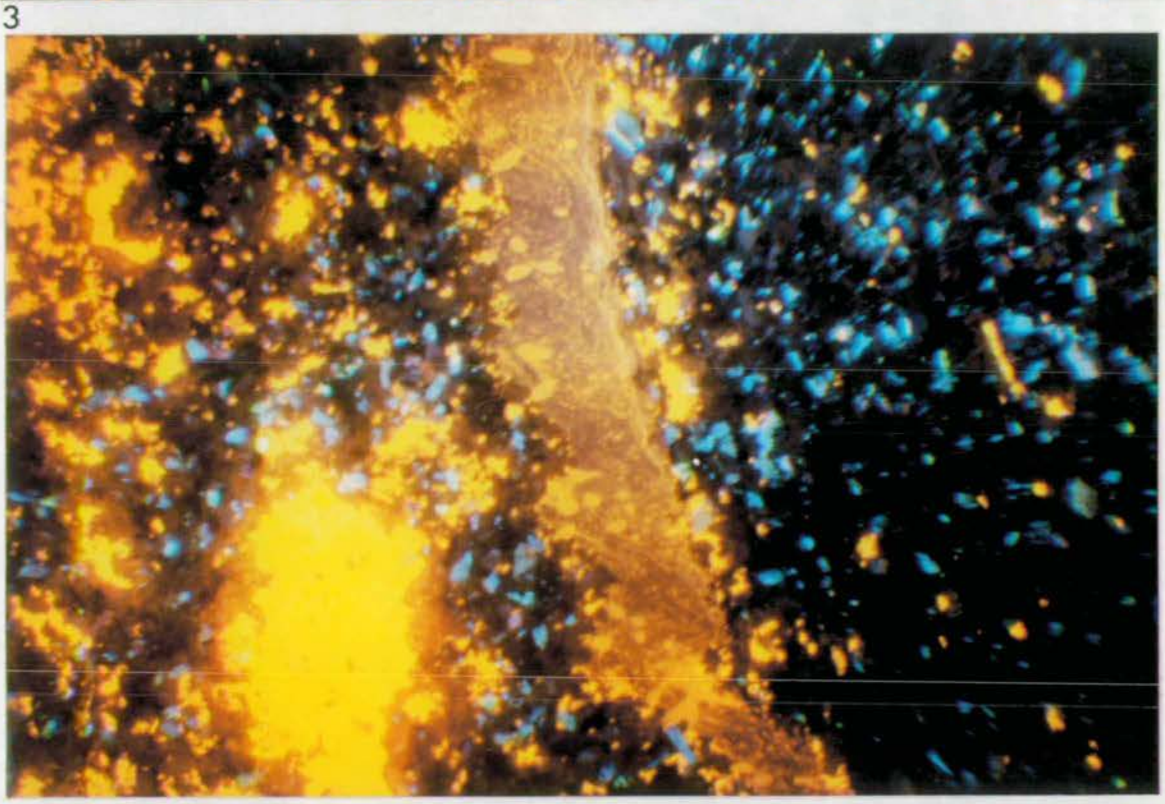


Plate 3.10

NEWLANDS CONGLOMERATE

Figure

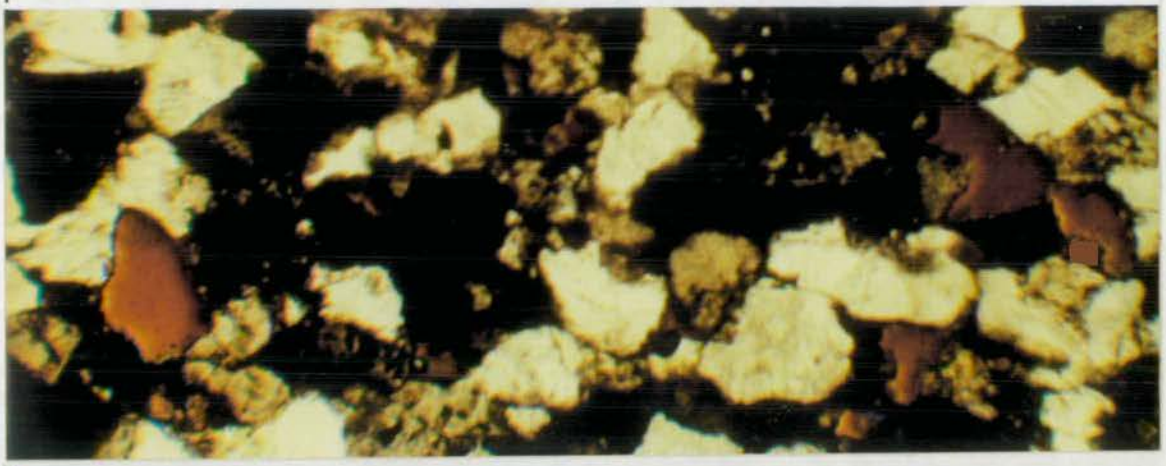
1. Poorly-sorted, coarse-grained lithic arenite.
   TW.98.187. Scale: bar represents 1 mm, *Tr.L.* x *Pol*.

2. Under CL, quartz is seen to be dominant luminescing purple and brown, accounting for as much as 70% of the total volume, while feldspars, luminescing blue, account for less than 10%. Lithic clasts are mostly revealed as quartz-feldspar aggregates, probably of igneous origin. Since the grains are closely packed, some show grain-to-grain contacts.
   TW.98.187. Scale: bar represents 1 mm, *CL*.

3. Some of the quartz grains show narrow fractures filled with dark-brown secondary quartz. Quartz overgrowths on some grains are evident. Yellow-luminescing apatite grains occur near the centre of the field of view. In the top centre a feldspar activated by Fe^{3+} luminesces red.
   TW.89.187. Scale: bar represents 1 mm, *CL*.

PLATE 3.10

1



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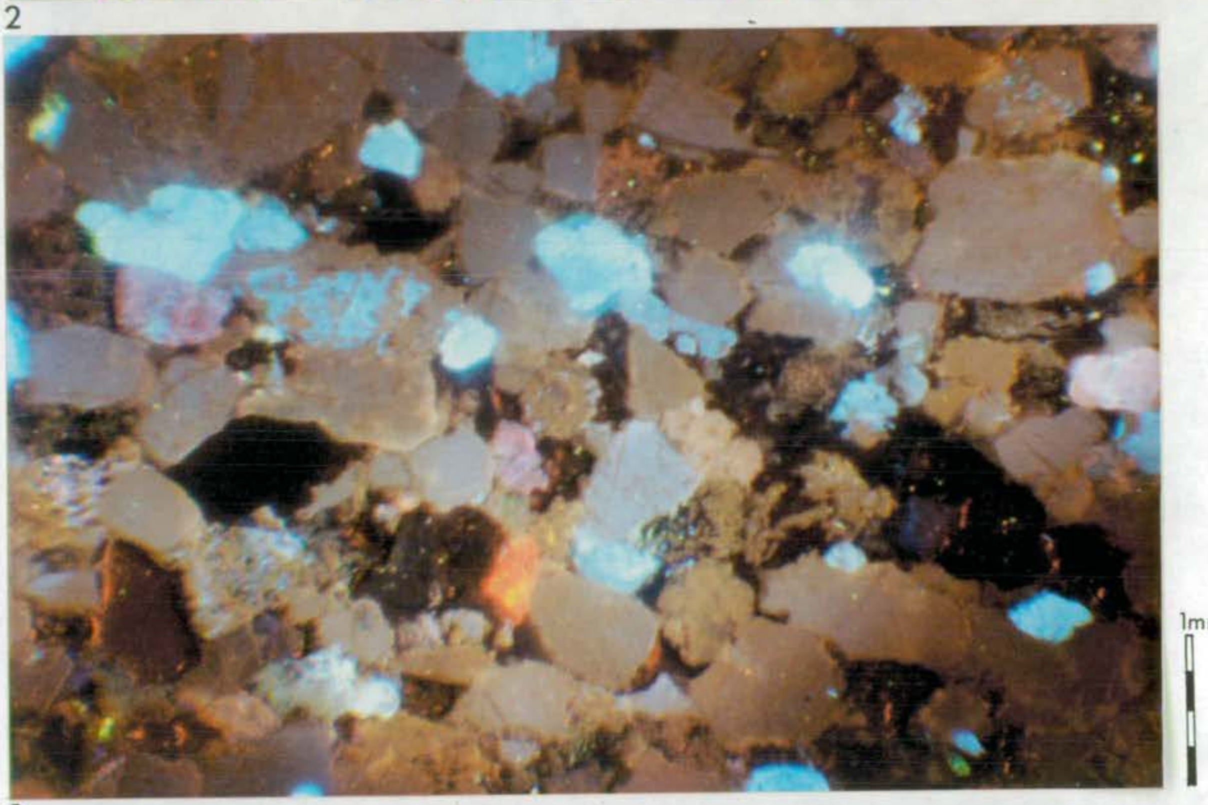

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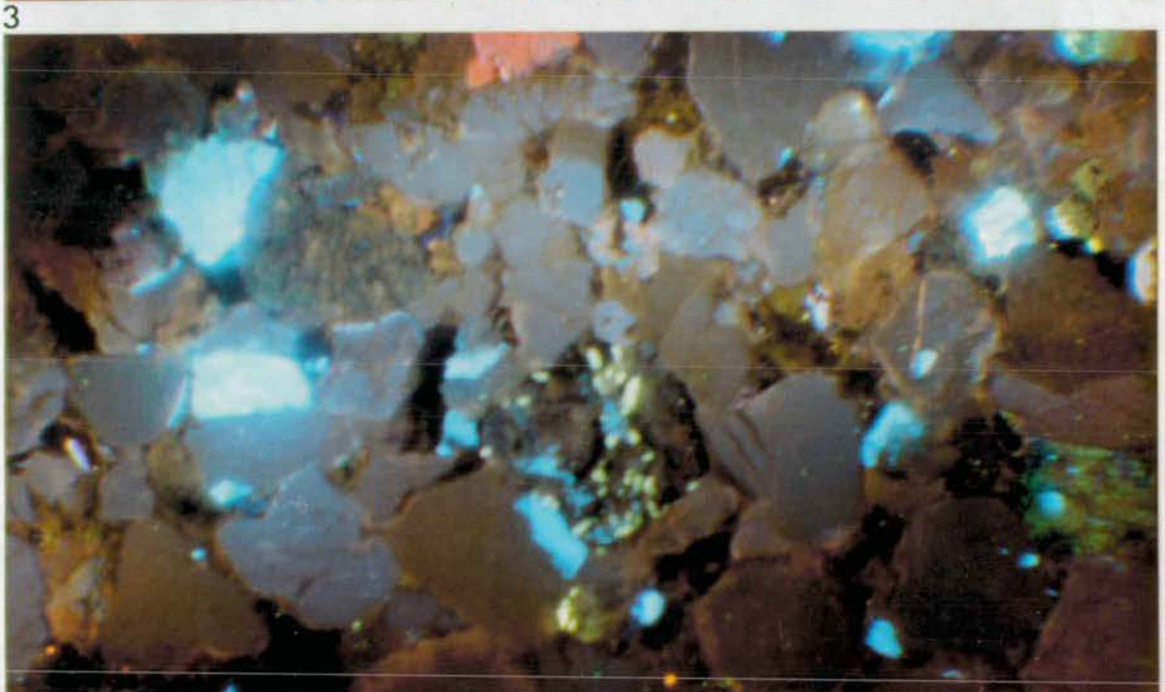


Plate 3.11

GLENWELLS BURN CONGLOMERATE 2

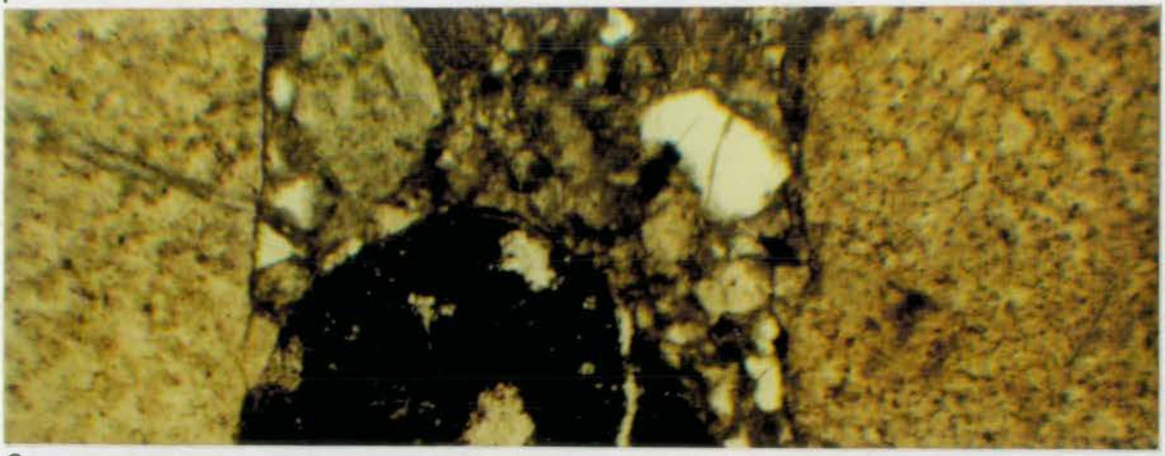
Figure

1. Pebbly conglomerate showing the contact between three large pebbles.
TW.98.188. Scale: bar represents 1 mm, *Tr.L*.

2. Under CL the left-hand pebble is dominantly quartz; the centre pebble is quartz and non-luminescent mafic minerals with subsidiary blue luminescent feldspar. The right-hand pebble is a fine-grained feldspar-quartz mosaic. Between the pebbles the matrix has allowed penetration of burial fluid which has deposited calcite, with orange CL, along compaction-fractures in the clasts.
Scale: bar represents 1 mm, *CL*.

3. A large quartzite pebble occurring in a feldspar-rich (luminescing blue) groundmass. The quartzite exhibits a number of conjugate compaction fractures which have been infilled with orange-luminescing calcite.
TW.98.188. Scale: bar represents 1 mm, *CL*.

1



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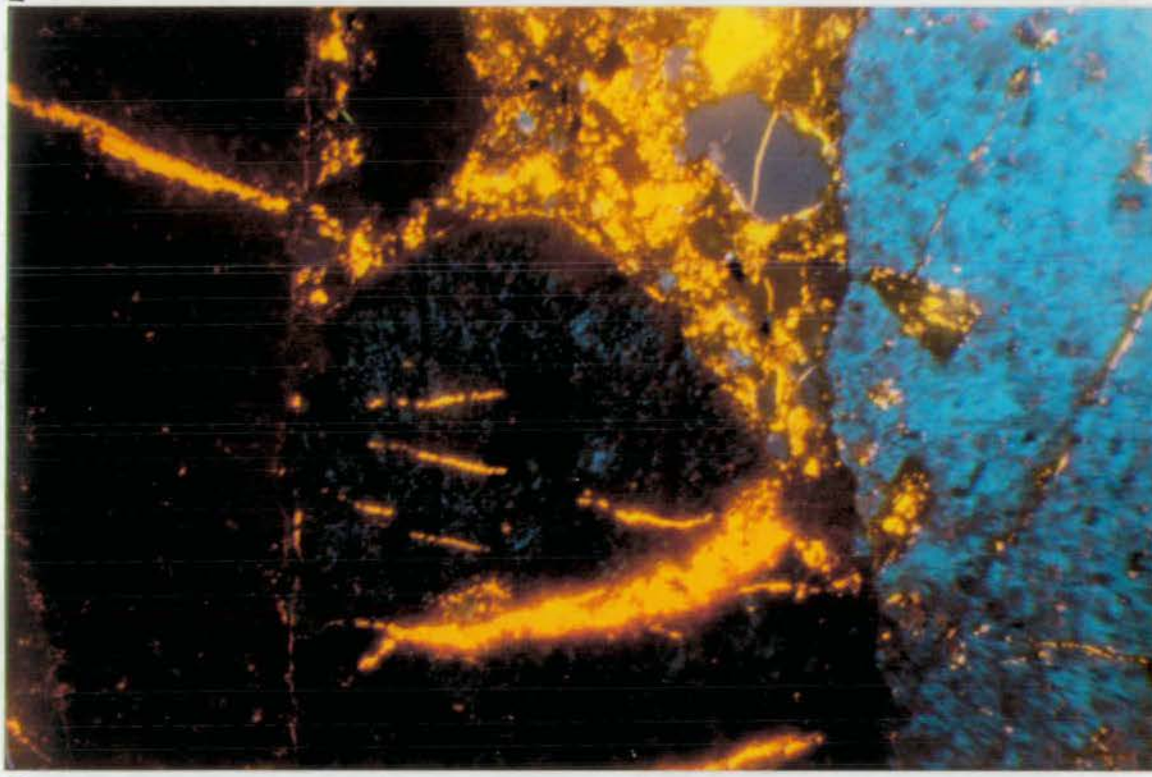


1mm

3

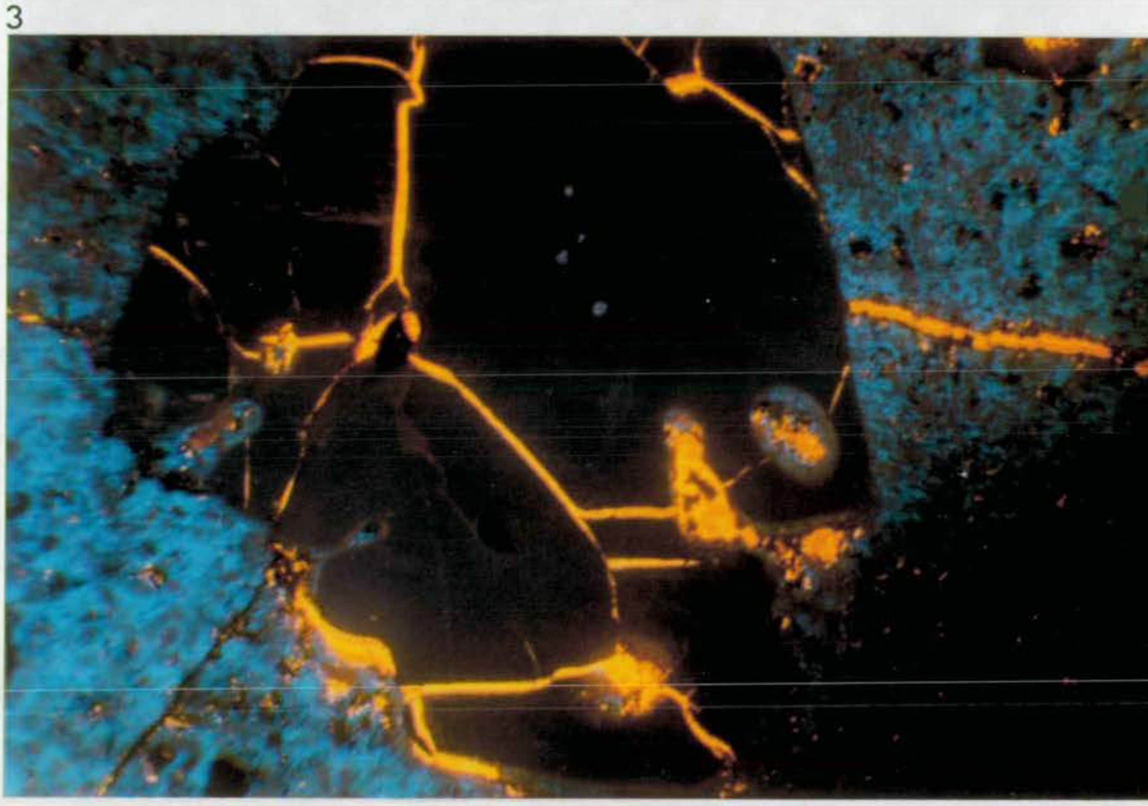


Plate 3.12

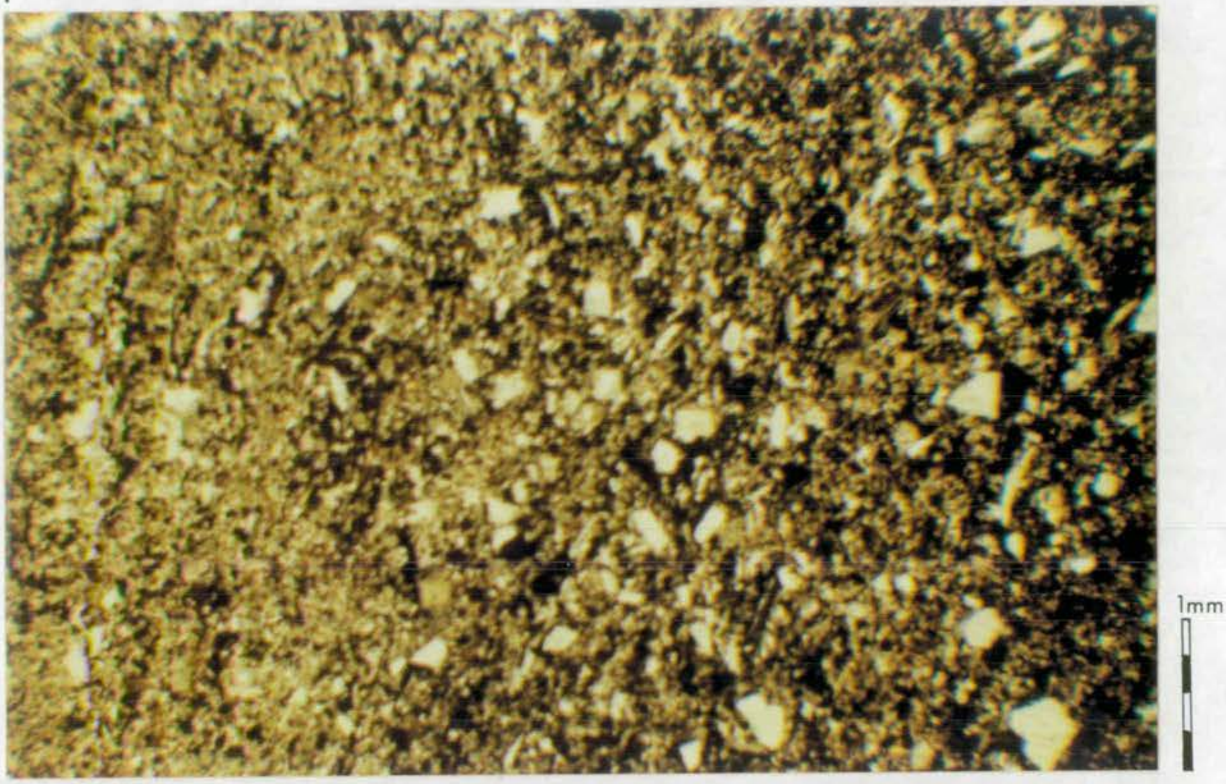
NEWLANDS FORMATION

Figure

1. Poorly-sorted siltstone.
   TW.124.189. Scale: bar represents 1 mm, *Tr.L.*

2. Under CL, plagioclase feldspar is seen to be abundant, luminescing pale blue. Large red-brown luminescing quartz grains suggest a metamorphic origin. Very small apatite grains which would have normally been overlooked in transmitted light luminesce yellow. Deep royal blue CL is attributed to kaolinite/dickite forming as a burial cement/ replacement. En echelon tension veinlets are revealed by bright orange calcite cement, and a similar cement is disseminated in the matrix.
   TW.124.189. Scale: bar represents 1 mm, *CL*.

1



2

Plate 3.13

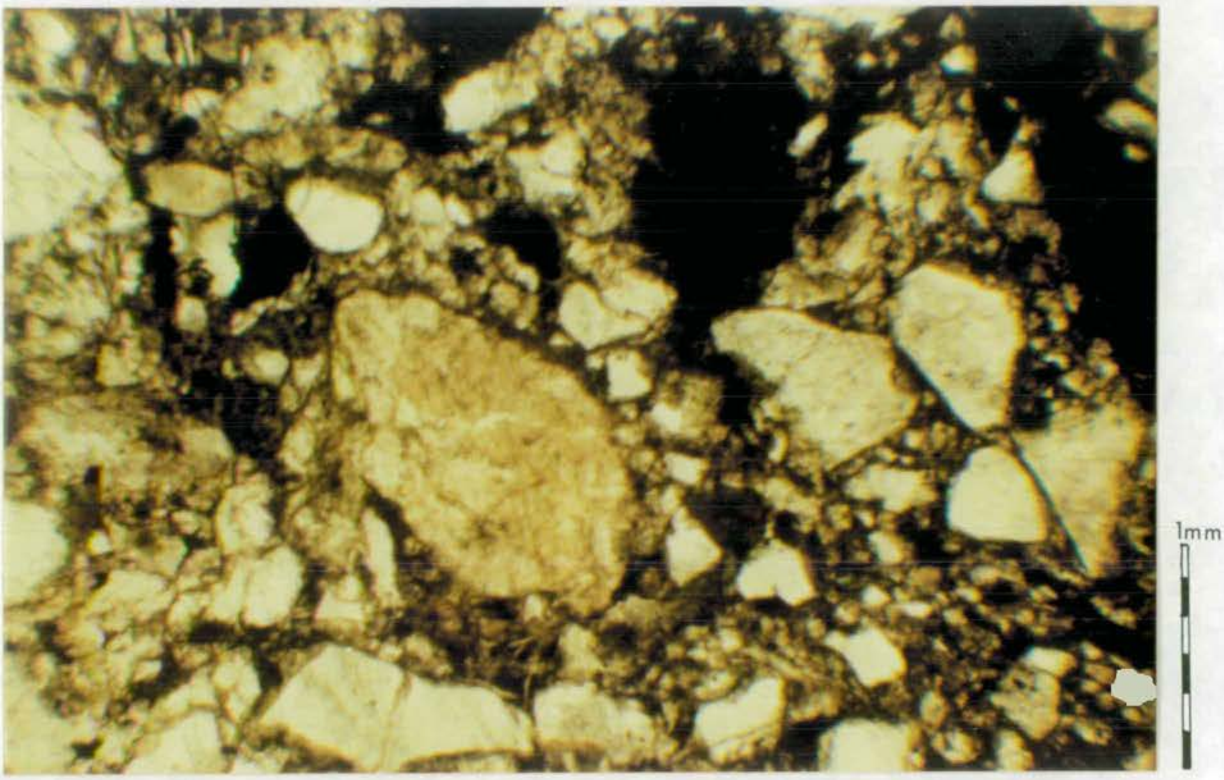
UPPER SAUGH HILL GRIT FORMATION

Figure

1. Poorly-sorted, coarse-grained sandstone.
   TW.146.190. Scale: bar represents 1 mm, *Tr.L.*

2. What appear as single quartz grains under CL are revealed as lithic fragments including quartz/feldspar rocks and quartzite clasts with many fused sub-grains. Light pinks, reds and blues are varieties of feldspar, whilst the accessory mineral apatite is bright yellow-green.
   TW.146.190. Scale: bar represents 1 mm, *CL*.

1



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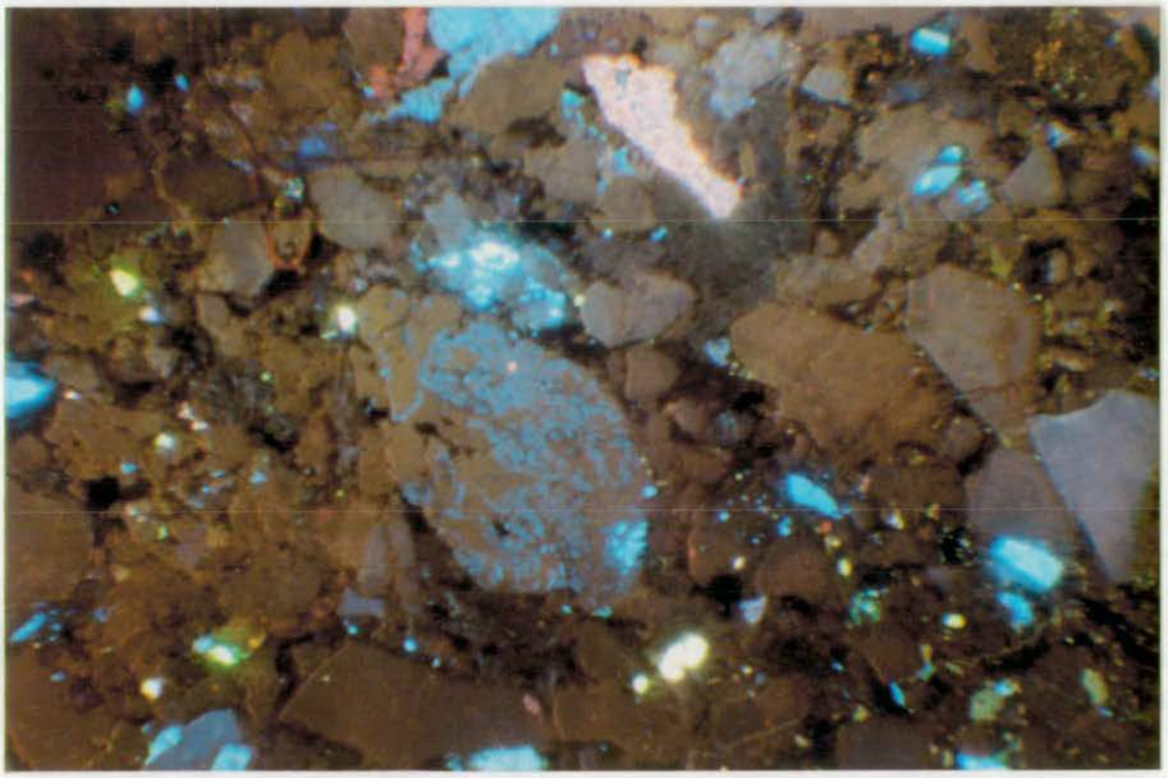


CHAPTER 6

6. PETROGRAPHIC DESCRIPTIONS OF THE SEDIMENTS OF THE COASTAL SECTION

6.1 DESCRIPTIONS AND INTERPRETATIONS

6.1.1 Craigskelly Conglomerate Formation

Section Nos: TW.204.166 to 170

Type: Medium- to coarse-grained lithic arenite

Locality: 204, Craigskelly, Coastal Section

Description:

In the Craigskelly Conglomerate the sandstones vary from coarse-grained to medium-grained but they are generally similar in compositional character. The description below is amalgamated from a study of ten thin sections.

The green coloured sandstones are poorly sorted and are composed of quartz (c. 13%), lithic fragments (c. 65%), feldspar (2%), mica (5%) (Fig. 6.1 and 6.2) and are bound by a chemically precipitated cement of quartz and calcite set in a matrix of clay minerals.

Grain size ranges from 0.1-12.0mm, averaging 0.3mm diameter (medium sand grade) and grains are usually of low sphericity and are angular-subrounded (Plates 4.1.1 and 2). Both monocrystalline and polycrystalline quartz are present. Tabulate to elongate shaped monocrystalline quartz crystals show straight and undulose extinction, with some grains containing rounded inclusions (Plates 4.1.3 and 4). The polycrystalline quartz are of typical metamorphic origin and are composed of multiple crystals with both uneven rounded sutures and elongated, sheared quartz crystals. Occasionally quartz exhibits feldspar overgrowths.

A great diversity of clast types is present, derived from metamorphic, igneous and sedimentary rocks. Schistose quartz clasts are composed of sheared crystals and aligned mica, whilst another metamorphic clast had a distinct platy foliation and must originally have been either a shale or slate. There are also single grains of yellow-coloured epidote. The igneous clasts range from basic to intermediate (Plate 4.1.5). Andesitic volcanics contain plagioclase phenocrysts, partially replaced by sericite and very pale green pseudomorphs suggesting replacement of the pyroxene phenocrysts. Other acidic igneous clasts are of granite or granodiorite with granophyric textures. Cherty microcrystalline quartz is also present, as is jasper. Rarely there are reworked poorly-sorted siltstone clasts in which the detrital monocrystalline quartz, of low sphericity, does not exceed 0.05mm. Rectangular to tabulate shaped feldspars not exceeding 0.2mm in diameter range from fresh to very altered (mainly sericitized)

FIGURE 6.2

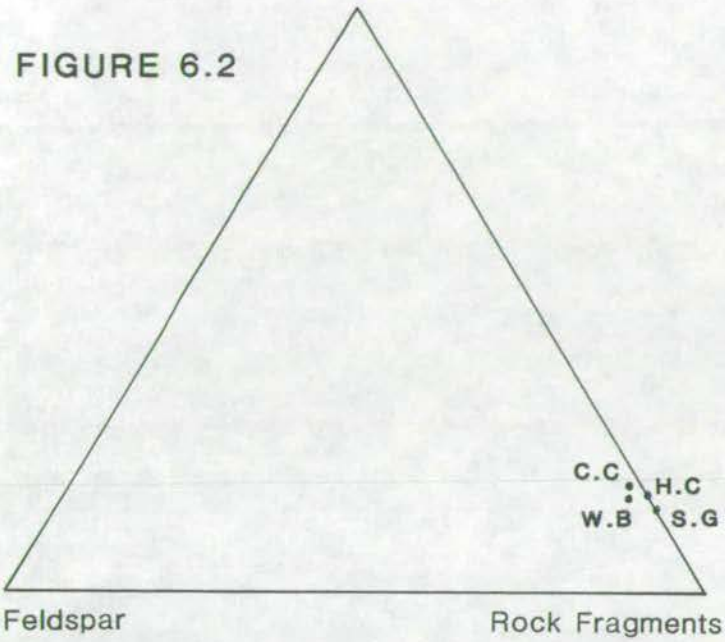
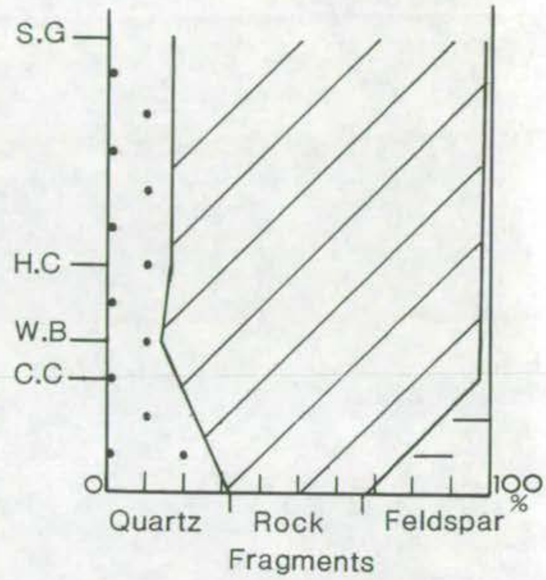


FIGURE 6.3



Fig(6.2) Constituents of the Formations plotted on a ternary diagram (Q.F.R).

Fig(6.3) Vertical change in the percentages of Quartz,Rock Fragment and Feldspar content.

FIGURE 6.1

Constituents	Formation			
	C.C	W.B	H.C	S.G
Quartz	12	4	13	11
Rock Fragments	57	26	65	53
Feldspar	2	O	O	1
Oxide	O	O	O	1
Quartz Cement	2	O	O	O
Mica	5	2	2	7
Clay	18	31	7	8
Calcite Cement	4	37	13	18
Porosity	O	O	O	O
Olivine	O	O	O	O

Fig (6.1) Table of constituent percentages of very coarse-grained sandstones (300 point counts per thin section).

resulting in a cloudy appearance, yet twinning may be partially preserved (Plate 4.1.6). The feldspars are mainly lamellar twinned plagioclase and cross hatch twinned microcline.

The clasts are fairly densely packed and subsequently the matrix is less than 18%. Clay minerals, including kaolinite, chlorite, illite and sericite, are the main constituents of the matrix, and are patchily distributed, infilling pockets between the grains. The matrix originates from the in situ alteration of unstable minerals and is thus secondary.

A chemical precipitate of quartz binds the sediment together - occurring as authigenic quartz overgrowths and as a meniscus fabric at grain to grain contacts.

Fracturing is found in some grains and the fractures are commonly infilled with quartz (Plate 4.1.7). In other veins calcite entirely fills the very thin fractures.

Higher up in the sandstone of locality 204 (TW.204.168) calcite occurs throughout, and can be seen to merge into the clasts and also alter the clast (Plate 4.1.8).

CL

Feldspar content is high, estimated at 25% (contrasting with the transmitted light point-count estimate of less than 5%) (Fig. 6.1 and Plate 4.5.1 and 2) and the colours range from green, blue to purple. Normally pressure-point solution is evident but in the case of the Craigskelly Conglomerate the grains are behaving in a brittle way and flames are commonly annealed with quartz. Either deformation in the form of fracturing occurred prior to deposition and the grains (containing the flames) were transported, or the fracturing occurred in situ. Since brittle fraction in the Craigskelly Conglomerate occurs at grain to grain contacts and the fractures are traced into adjacent grains, the fracturing occurred after deposition. This is also confirmed by fractured and annealed feldspars. Such different coloured feldspar originating from different sources could not all have been fractured prior to deposition. These fractures are thus the result of compaction.

Interpretation

Texturally and mineralogically, the conglomerates are immature. As with the Mulloch Hill Conglomerate, the sandstones are very poorly to poorly sorted, composed of angular to subangular grains bound in a matrix exceeding 5%. The presence of unstable particles such as feldspars and lithic fragments emphasises the immaturity, and the variety of lithic fragments reflects a wide provenance, suggesting a large drainage basin with a diverse bed-rock lithology, including granite, basalt, chert, dolerites microdiorites, fine-grained sandstones and siltstones, and metamorphic mica-schists.

6.1.2 Woodland Formation

Base

Section No: TW.206.171 to 172

Type: Pebbly coarse-grained breccia

Locality: 206, Craigskelly

Description:

The base of the Woodland Formation is formed by a poorly sorted, siliceous and calcareous cemented pebbly coarse-grained sandstone with quartz (c. 4%), lithic fragments (c. 26%), feldspar (c. <1%), and mica (c. 2%) (Fig. 6.1 and 6.2), bound in a clay matrix. The pebbles show no preferred orientation, nor is stratification evident.

Grain size varies from 0.02mm-14.00mm in diameter (sand to gravel grade). Quartz is mainly plutonic quartz although there are a number of polycrystalline stretched metamorphic quartz crystals with sutured edges, and volcanic quartz grains. These grains tend to be tabulate to elongate and fairly angular.

The lithic fragments include a few tabulate to elongate shaped dolerite clasts. Most of the igneous textures in the clasts are unrecognisable due to alteration (Plate 4.2.1). There are a few chert clasts. Rarely, reworked sedimentary calcareous cemented siltstones are present.

Feldspars are exceedingly rare, (c.<1%) and can be distinguished by their susceptibility to alteration, lamellar twinning, tabulate to rectangular shape and small size (i.e. 0.08mm).

The matrix (c. 31%) is derived from the in situ degradation of the major constituents and some grains are actually seen partially decomposed.

Whereas quartz cement is prominent in the form of authigenic quartz overgrowths and grain to grain contacts, calcite cementation is sparsely developed. The calcite does not form well-defined crystals nor is it twinned, and tends to form in patches (Plate 4.2.2). Moreover, fractures cutting through lithic fragments and quartz grains are infilled with calcite, and these cracks demonstrate tension gashing.

CL

The rock particles include igneous and metamorphic types, which have partially degenerated into kaolinite. Quartz clearly displays authigenic overgrowths and several stages of overgrowth can be detected showing different luminescence intensities. The feldspars are relatively abundant and very fine-grained, yielding a deeper blue luminescence colour than in the underlying Craigskelly Conglomerate and this may be related to a different source (Plate 4.6.1 and 2). Both the feldspars and the quartz grains contain thin fractures.

Larger fractures filled with vein-calcite cut through the kaolinite matrix, and cement. These tend to be clear phases (Plate 4.6.3).

Section No: TW.206.173

Type: Very fine-grained arenite

Locality: 206, Craigskelly

Description:

The conglomerate gradually fines upwards into yellowish-grey coloured fine-grained sandstones (Plate 4.2.3). The very fine-grained sandy laminae are composed of quartz, feldspar and lithic fragments, cemented primarily by calcite. Poor grain sorting is reflected by grain-size ranging from 0.06mm to approximately 1.0mm (sand grade) in diameter, and with an average 0.1mm diameter (very fine sand grade). Elongate to tabulate shaped angular to subangular quartz grains are surrounded by a calcareous cement. Monocrystalline plutonic quartz is dominant although there are a few sheared metamorphic quartz grains (composed of elongated, highly sutured polycrystalline quartz crystals) and schistose quartz containing mica flakes. Feldspars are exceedingly rare (less than 5%), and are mainly plagioclase. Lithic fragments are also inconspicuous, and are not very diverse in composition.

Occasionally black clay-rich flasers up to 2mm long are irregularly dispersed throughout the sediment. The boundary between this and the overlying laminae is sharp, and there is a marked reduction in grain size, ranging from 0.02-0.20mm (silt to sand grade), averaging about 0.06mm (coarse silt grade). The resulting texture is slightly better sorted, despite the irregular occurrence of some slightly larger clasts. Quartz is dominant, mainly monocrystalline plutonic quartz but occasionally sheared metamorphic polycrystalline quartz. The mica flakes (less than 1%) are up to 0.06mm long, and show a general preferred orientation parallel to bedding. Calcite is unevenly distributed throughout the sediment, and is very fine-grained.

The general brown colour, gives a slightly muddier appearance to the underlying sediment and the brown discontinous flasers, not exceeding 0.1mm, reflect clay-rich accumulations. Slightly finer-grained irregular-shaped concentrations are attributed to the possible effects of bioturbation.

Section No: TW.232.174

Type: Laminated mudstone

Locality: 232, Woodland Point

Description

The mudstones are finely laminated: laminations are defined by subtle grain-size and colour differences and by the presence or absence of fossil fragments (Plate

4.2.5). The non-fossiliferous layers are up to 0.5cm thick, generally a dusky yellow-green colour in which grain-size spans from 0.06mm to 0.32mm diameters, producing a moderately sorted texture. Elongate to tabulate shaped plutonic, monocrystalline quartz grains are abundant, often displaying a preferred orientation in which the elongate grains are parallel to bedding. Generally the degree of roundness is low, with grains usually angular to subrounded. Sheared metamorphic quartz grains are rare, tending not to be larger than 0.12mm in diameter, and feldspars are also few in number. Typically, plagioclase feldspar shows lamellar twinning, approximately 0.1mm (tabulate shaped), and microcline feldspar infrequently displays a perthitic texture.

Lithic fragments amount to less than c. 20% and are not very compositionally diverse. Igneous fragments include a small basalt clast, less than 0.32mm diameter.

The bioclastic yellow-green coloured mud is thicker (4.0mm thick) and slightly finer-grained - grain size ranges from 0.02-0.1mm (silt to sand grade), and is consequently better sorted. The lithology is slightly muddier in appearance due to the increase in matrix content. Plutonic monocrystalline quartz is dominant, typically tabulate to elongate in shape and fairly angular. Calcite is dissipated throughout, acting as the main cementing agent. Fossils include small (0.9mm diameter) crinoid ossicles, disarticulated brachiopod valves and bryozoans (Plate 4.2.4 and 5).

<u>Upper Member</u>

Section No: TW.216.175-176

Type: Fine-grained laminated shales

Locality: 216, Haven

<u>Description</u>:

The top of the Woodland Formation is represented by laminated shales. Three laminations can be recognised within the thin-section based upon differences in colour and subtle grain-size differences (Plate 4.2.6).

The light olive-grey coloured laminae are up to 2.5mm thick, composed of 0.03 to 0.06mm silt grains of low sphericity, dominantly elongate to tabulate shaped. Oval to round, darker-brown coloured concentrations (up to 0.5mm diameter) are composed of finer-grained material, which are most likely to represent burrows. In contrast with the Newlands Formation (Craighead) there are no concentrations of coarser material on the circumference of the outer wall. Calcite occurs as a secondary cementation agent.

The medium olive-grey coloured laminae are thinner, varying from 0.5 to 1.5mm wide. Maximum grain size is approximately 0.06mm (silt grade). Being much dirtier in appearance due to the subtle increase in clay matrix, these laminae are composed of elongate to tabulate shaped monocrystalline plutonic quartz, with concentrations of opaques and mica flakes aligned preferentially.

The very pale coloured, much cleaner laminations are between 1.5 to 2.0mm wide containing grains ranging in size from 0.02 to 0.1mm (silt to sand grade) in diameter, averaging 0.06mm (silt-sand grade) in diameter. Noticeably more detrital, tabulate to elongate shaped quartz is present, as well as sheared metamorphic quartz, mica and opaques. These laminae have a fairly sharp contact with the overlying light olive-grey laminae.

A number of small fractures delicately displace the laminations, up to 1.0mm thick (although thickness does vary) (Plate 4.2.7). Running obliquely, the displacement measures up to 0.5 to 2.0mm long and is infilled with calcite, which is not typically lenticular in shape. Within the calcite there are a few fine-grained silt grains of quartz.

Furthermore there is evidence of slumping, involving very pale coloured quartz-rich laminae sinking gently into the light olive-grey shale.

Interpretation

A reduction in grain size and slight change in clast composition marks the gradual transition from the Craigskelly Conglomerate to the overlying Woodland Formation (Fig. 6.3). Source area lithology consisted of igneous rocks, cherts, low-grade metamorphic mica schists and calcareous-cemented siltstones. Ferroan calcite, (staining blue when immersed in a solution of Alizarin Red and Potassium ferricyanide) is far more abundant and acts as a cementing agent and void-filling mineral. Precipitation of calcite cement was presumably dependent on an altered carbonate-biocarbonate ratio in the interstitial waters. Conditions promoting calcite cementation require increasing either temperature or pH, both of which decrease the solubility of calcite. Usually calcite cementation post-dates secondary quartz cements in the same rock. The fractures represent tension gashes caused by compaction and deformation.

With the gradual erosion of the hinterland the breccia fines upwards. Texturally and mineralogically, the siltstones still remain immature. The persistence of calcite indicates saline shallow marine conditions, as does the mottled appearance attributed to bioturbation. Oxidation levels at the sediment-water interface, and immediately below, must have been sufficiently high enough to support an infauna. It is clearly evident that bioturbation disrupts the preferred orientation of the minerals, hence fissility in the siltstone is poorly developed. The finely laminated shales at the top of the Woodland Formation represent the products of dilute turbidites, specifically Td-Te Bouma sequences. The light-olive coloured, finer-grained and better sorted laminae were deposited by the dilute tails of high density turbidite current whereas the medium olive coloured laminae, slightly-coarser grained and less well sorted were deposited by the settling out of the mud.

Many of the laminations have been displaced by microfaults, implying that the shales must have been partially lithified prior to faulting.

6.1.3 <u>Haven Conglomerate</u>

Section No: TW.218.177-180

Type: Pebbly medium-grained lithic arenite

Locality: 218, The Haven

<u>Description</u>:

The Haven pebbly sandstones are characterised by a poorly-sorted coarse- to medium-grained aggregate of quartz (c. 13%), lithic fragments (c. 65%), feldspar (<1%) and mica (c. 2%) grains (Fig. 6.1 and 6.2), cemented dominantly by quartz and set in a matrix of clay. Internally, there is no organisation of clasts and the lithology is unfossiliferous.

The detrital grains range in size from 0.06mm to 5.0mm, with an average of approximately 0.3mm (medium sand grade) (Plate 4.3.1). Plutonic quartz, distinguished by straight to undulose extinction, having crystals tabulate to elongate in shape and varying from angular to subrounded, is dominant (Plate 4.3.2). The quartz rarely shows euhedral growths indicative of authigenic quartz cementation, and the grains are sometimes seen to be coated with very thin clay films. Rarely semi-composite quartz possessing abundant vacuoles and recrystallised metamorphic quartz (Plate 4.3.3) are present.

The diversity of lithic fragments is low, but these include very fine-grained siltstone clasts, (Plate 4.3.4); calcareous cemented fine-grained sandstones; a few igneous clasts, such as trachytes, polycrystalline quartz displaying definite metamorphic foliation, abundant small clasts of mica schist, brown clasts of micaceous schist/shale, and cherty microcrystalline quartz.

Feldspar is scarce, crystals are noticeably smaller in size (0.1-0.2mm) and tabulate to rectangular in shape. They are generally twinned plagioclase feldspar (Plate 4.3.5). Some of the micaceous clasts (white muscovite) are deformed as a result of compaction. Accounting for less than 7%, the matrix is composed of clay material, namely kaolinite, illite and chlorite. Due to the in situ degradation of the constituent grains, the matrix tends to accumulate in pockets.

Siliceous cementation occurs at grain to grain contacts, exhibiting both straight and concavo-convex boundaries between grains (Plate 4.3.6). Secondary cementation is composed of calcite, which is patchily developed, infilling both empty pores and fractures, and occasionally seen corroding quartz and feldspar grains. Calcite cement accounts for as much as 13%. Occasionally developed in the Haven Conglomerate there are fine-grained quartz arenites.

Section No: TW.218.179
Type: Fine-grained lithic arenite
Locality: as above

Description:

This moderately-sorted, medium-grained sandstone consists of quartz (c. 15%), lithic fragments (c. 58%), feldspar (c. 1%), opaques (c. 1%) and mica (c. 2%) grains in a siliceous cement and set in a clay-rich matrix.

Grain size measurements range from 0.04mm to 1.8mm (silt to sandstone) but generally occur round about 0.1mm (very fine sand grade). Tabulate to elongate shaped quartz grains are fairly angular. As with the conglomerate, monocrystalline quartz is dominant, specifically plutonic and volcanic quartz, with a few recrystallised quartz grains of metamorphic type. Even though the lithology is moderately to well sorted, there are few anomalously large plutonic quartz grains measuring 1.8mm.

Lithic fragments and feldspars are less abundant than in the coarser-grained counterpart. However there is a slight increase in the abundance of thin mica flakes (Plates 4.3.7). The mica flakes are up to 0.1mm long, but do not show any preferred orientation.

The overall clean appearance of the sandstone is a result of the small amount of matrix (c. 5%). Consequently the grains are relatively closely packed, almost clast-supported. In places grading is well developed (Plate 4.3.7).

CL

Clast composition in the Haven Conglomerate is dominated by quartzite pebbles showing uniform luminescence colours. Moreover, the apatite is a distinctive green colour (Plate 4.7.1) markedly different from the yellow epidotes in the Craighead Inlier. This difference in colour may be related to differing source areas. Generally feldspars are few, accounting for less than 5%, and are characterised by a blue CL colour (Plate 4.7.2).

Interpretation

The sudden increase in grain size is accompanied by an influx of a fairly diverse assemblage of lithic fragments. These changes may relate to a rejuvenation of the source area. This source area was rich in metamorphics, also chert and sedimentary rocks such as siltstones. The mica may have been derived from mica-bearing granites and gneisses. Mineralogical immaturity, indicated by the presence of unstable lithic fragments, and textural immaturity, reflected by the poor sorting, are concordant with rapid deposition of the sediments. Some of the sedimentary fragments are identified with those in the underlying Woodland Formation. Thus the underlying substratum must have been eroded and consequently incorporated into the succeeding sediment.

Gradually there is a decrease in grain size, indicating settling of the finer-grained material, and occasionally the sandstones are graded. Apart from the reduction in the content of lithic fragments, there is no dramatic change in the composition of the sandstones, and consequently no change in the lithology of the source area. Thus it appears that the hinterland providing the detritus was being slowly eroded down. Despite their higher density and large size and because of their flakey shape, the mica crystals tend to collect in the sandstone, accounting for the increase in mica content.

6.2.4 Scart Grit Formation

Base

Section No: TW.225.183

Type: Pebbly medium-grained lithic arenite

Locality: 225, Woodland Point

Description:

At the base of the exposed Scart Grits, locality 225, there are a number of pebbly sandstones. These poorly sorted sandstones are coarse- to medium grained, containing small pebbles, of quartz (c. 15%), lithic fragments (c. 60%), feldspar (c. 1%) and opaque minerals grains (c. 1%), cemented dominantly by authigenic quartz and set in a matrix of clay (Plates 4.4.1 and 2).

Grain size varies from 0.1mm to 11.0mm, averaging about 0.2-0.4mm (medium sand grade). Tabulate to elongate shaped, sub-angular, subrounded quartz grains dominate the lithology. Specifically plutonic quartz is dominant, with only a few recrystallised metamorphic grains and elongated stretched metamorphic fragments, not exceeding 0.5mm and 2.5mm diameter respectively. Lithic fragments include poorly-sorted, medium-grained (0.08-0.1mm diameter) sandstone clasts (Plate 4.4.3) and basalt and chert clasts with a thin vein of quartz infill.

Feldspar, namely plagioclase and sanidine, is rather inconspicuous and scarce, and ranges from fresh to very altered. The feldspars are usually tabulate to rectangular in shape and are noticeably smaller than the quartz fragments (0.1mm diameter). Matrix is composed of the in situ breakdown products of the larger unstable clasts, resulting in a residual clay accumulation in little pockets.

Middle Member

Section No: TW.226.181 and 182

Type: Medium grained lithic arenite

Locality: 226, Woodland Point

Description:

The coarse- to medium-grained sandstones representing the middle member of the Scart Grits are represented by lithic arenite. The main constituents are quartz (c. 13%), lithic fragments (c. 50%), feldspar (c. 1%) and mica (c. 5%) grains cemented dominantly by quartz, and secondary calcite and set in a matrix of clay.

Averaging roughly 0.2-0.4mm (medium sand grade) in diameter, the light-brown coloured sandstone grains range from 0.08mm to 1.6mm diameter (sand grade) and the texture is poorly sorted (Plate 4.4.4). Quartz fragments, mainly monocrystalline tabulate to elongate shaped plutonic quartz, and rarely vein and sheared metamorphic quartz, are angular to subrounded.

Feldspars are rare, accounting for less than 5% of the rock, composed of tabulate to rectangular shaped twinned plagioclase crystals not exceeding 1.7mm, and small (approximately 0.2mm) tabulate shaped microcline feldspar. They vary from fresh to fairly altered. The lithic fragments include basalts, schistose quartz up to 1.9mm long, and medium-grained siltstone clasts.

The matrix is derived from the in situ alteration of unstable minerals, infilling pockets between the grains, and is composed of a mixture of chlorite, illite and kaolinite.

Cementation is dominantly siliceous in the form of authigenic quartz overgrowths. No internal sedimentary structures such as grading are evident nor were fossil fragments found.

Upper Member

Section No: TW.226.184

Type: Pebbly medium-grained lithic arenite

Locality: 226, Woodland Point

Description:

The top of the Scart Grits is characterised by pebbly, poorly-sorted sandstone composed of quartz (c. 11%), lithic fragments (c. 53%), feldspar (c. 1%) mica (7%) (Fig. 6.1 and 6.2). It is cemented primarily by quartz, with secondary calcite cement, and bound in a clay matrix. No internal organisation is apparent nor were fossils recovered.

Grain size varies from 0.02mm to 3.0mm diameter (silt to granule grade), averaging 0.4mm (medium sand grade) in the sandstones, whereas the pebble clasts do not exceed 20mm in diameter (Plate 4.4.5). Tabulate to elongate shaped monocrystalline plutonic quartz is dominant, but stretched, sheared and recrystallised quartz crystals are present. Many of these grains are angular to subrounded.

Feldspar (c. 1%) ranges from altered to highly sericitised and fragments tend to be much smaller than the surrounding quartz grains with tabulate to rectangular shaped pieces less than 1.5mm in diameter. Composition of feldspars includes plagioclase and sanidine (Plate 4.4.6).

The lithic fragments are fairly diverse including mainly polycrystalline quartz with sutured internal boundaries, occasionally with a metamorphic foliation; smaller elongate clasts of quartz-mica-schist; and variably fine-grained igneous clasts, such as brown coloured clasts which were originally feldspar-rich volcanics. Unfortunately they are so highly altered, through surface weathering, that the original texture is almost unrecognisable. It was possibly andesite. Also there are a few clasts of microcrystalline quartz. Sedimentary rock fragments are very scarce and those that do occur tend to be reworked poorly-sorted fine-grained sandstones.

Due to the fairly high matrix content (c. 8%) the sandstone is generally matrix supported. As with the rest of the sediments, the matrix is largely composed of clay material, which originates from the breakdown of the unstable constituent clasts.

Quartz cement is dominant in the form of authigenic quartz overgrowths at grain to grain contacts. Patchily developed throughout, calcite cement is present and is also seen actively eroding feldspar and quartz grains. Calcite crystals are up to 2.4mm in diameter, thus are very coarsely crystalline. Any internal organisation of the sediment such as stratification is apparently lacking.

CL

The Scart Grits are poorly-sorted, composed of a less diverse rock fragment assemblage than the Craigskelly Conglomerate. Constituents include igneous quartz grains, feldspar, mica and green CL-coloured apatite. Corrosion of the grains by carbonate produces secondary angularity (Plate 4.8.1), and dissolution and replacement of feldspar by carbonate is common. CL analysis was fundamental in detecting the presence of fossils, this in otherwise apparently unfossiliferous sandstone (Plate 4.8.2). During field and petrographic work no fossils were found in the Scart Grits. However by using CL a few fossil fragments were discovered, namely a crinoid ossicle and a disarticulated brachiopod valve.

Interpretation

Recording the gradual erosion of the source area, the Scart Grits Formation is finer-grained than the sandstones in the Haven Conglomerate. Furthermore the grains are slightly better rounded and sorted due to a longer transportation history, yet they are still texturally immature. In the lower beds randomly orientated small pebble clasts are found (namely products of pulses). Presumably the source area was still providing chert, vein quartz, calcareous-cemented siltstones and metamorphic mica-schists. Presence of these unstable rock fragments again indicates mineralogical immaturity. Stratigraphically higher, there is a reduction in grain-size and absence of pebbles associated with the settling of finer material, related to the source area which was capable of providing only very fine-grained detritus.

The pebbly sandstone contrasts with the underlying sandstones . Not only is there a distinct change in colour from light-pale brown to a light-grey colour but there are also a few petrographical differences. After approximately 15m of coarse- to medium-grained sandstone averaging 0.2-0.4mm in diameter, the increase in grain-size of the pebbly sandstones is very sudden , and clasts may be up to 8cm in diameter. Additionally there is a slight increase in the diversity of lithic fragments which include polycrystalline quartz, quartzose schists, cherts and dolerites, and abundant mica, yet feldspar content is very low. Likewise the clasts are elongate to tabulate sharp-angular to subangular and embedded in a clay matrix. In both, the main cementing agent is quartz, but in the pebbly sandstones calcite cementation is also active. These petrographical differences confirm the need to subdivide the pebbly sandstones into a distinct member. Since the horizon is not thick and overlain by finer grained sandstones this was only a minor local event.

6.2 COMPARISONS OF THE SEDIMENTS OF THE CRAIGHEAD INLIER AND THE COASTAL SECTIONS

The biostratigraphy of the Craighead Inlier and coastal sections was first established by Lapworth, based upon graptolite zonation, and most recently revised by Cocks and Toghill (1973). The lack of fossils from some parts of the sequence, for example the Mulloch Hill and Craigskelly Conglomerates, hinders correlation between the two study areas. Lithostratigraphic data has to be supplemented by sedimentological and petrographical studies in confirming mutual relations between formations of presumed equivalent age. When petrographic comparisons are made, features such as texture, mineralogy and deformation, are taken into consideration.

Below, comparisons are made between Formations from the Craighead and coastal section.

6.2.1 Mulloch Hill Conglomerate compared with the Craigskelly Conglomerate Formations

The Mulloch Hill Conglomerate sandstones are greyish-red in colour contrasting with the greyish olive-green colour of the Craigskelly sandstones. Both Formations have sandstones ranging in grain-size from medium- to coarse-grained (Fig. 6.4 and 6.5). Texturally both are immature, being poorly sorted and composed of angular to subangular, elongate to tabulate shaped clasts (Fig. 6.6 and 6.7). There is however a slight difference in the amount of matrix present, whereby the Mulloch Hill Conglomerate sandstones (c. 21%) have slightly more matrix as compared with that of the Craigskelly sandstones (c. 18%). Likewise the matrix is composed of the in situ breakdown of the constituent grains, accumulating in pockets between grains. The clay matrix consists of kaolinite, chlorite and illite.

Both sandstones are composed of quartz, feldspars, lithic fragments. Monocrystalline plutonic quartz is the dominant type of quartz (MH=19%) (Craig=12%), but polycrystalline quartz occurs in both in fairly high proportions. Some of the quartz contains small inclusions, lenticular rutile clasts, and graphic intergrowths of quartz and feldspar.

Superficially the feldspars are less abundant (MH=3%) (Craig=2%) and composed of tabulate to rectangular shaped lamellar-twinned plagioclase, and cross-hatched microcline and orthoclase. Under CL, however, feldspars account for as much as MH=20%, Craig=25%, and are similarly green-blue and buff coloured, although the feldspars in the Craigskelly Conglomerate luminesce slightly more purple in colour. Feldspars are noticeably smaller than the quartz grains and vary from fresh to very altered. Rarely myrmekitic textures are developed in feldspar from both sandstones. Lithic fragments are relatively abundant (MH=45%)

CRAIGHEAD

A

Formation	Grain size (in mm) Maximum	Minimum	Mean	Sorting
Upper Saugh Hill Grit Fm.	0.80	0.04	0.20	very poor
Glenshalloch Shale Fm.	0.09	0.01	0.01	moderate
Newlands Fm.	0.25	0.04	0.10	poor
Glenwells Burn Conglomerate 2	17.00	0.02	0.03	poor
Glenwells Burn Conglomerate 1	0.90	0.06	0.40	moderate
Newlands Conglomerate	18.00	0.25	0.50	poor
Glenwells Shale Fm.	0.20	0.01	0.01	moderate
Mulloch Hill Fm.	0.30	0.02	0.10	poor
Mulloch Hill Conglomerate Fm.	12.00	0.20	1.00	very poor

GIRVAN COAST

B

Formation	Grain size (in mm) Maximum	Minimum	Mean	Sorting
Scart Grit Fm.	11.00	060	0.20	poor
Haven Conglomerate	5.00	0.06	0.30	very poor
Woodland Fm.	0.20	0.02	0.06	moderate
Craigskelly Conglomerate Fm.	12.00	0.10	0.03	very poor

Fig(6.4) Grain size variations in the Formations in the Craighead Inlier and Girvan shore.

CRAIGHEAD

A

Formation	Roundness	Sphericity
Upper Saugh Hill Grit Fm.	angular-subangular	low
Glenshalloch Shale Fm.	subrounded	low-moderate
Newlands Fm.	angular-subrounded	low
Glenwells Burn Conglomerate 2	angular-subangular	low
Glenwells Burn Conglomerate 1	angular-subangular	low
Newlands Conglomerate	angular-subangular	low
Glenwells Shale Fm.	subrounded	low-moderate
Mulloch Hill Fm.	angular-subrounded	low
Mulloch Hill Conglomerate Fm.	angular	low

GIRVAN COAST

B

Formation	Roundness	Sphericity
Scart Grit Fm.	angular-subrounded	low-moderate
Haven Conglomerate	angular-subangular	low
Woodland Fm.	subrounded	low-moderate
Craigskelly Conglomerate Fm.	angular	low

Fig(6.5) Roundness and sphericity of the clasts in the Formations in the Craighead Inlier and Girvan Shore.

(Craig=57%) and diverse, including fine-grained basalts, andesites, dolerites, microdiorites, granites and cherts. Also there is a significant presence of metamorphics namely quartzitic schists, mica-schists, epidote and platey schists. Sedimentary clasts, such as reworked siltstone and very fine-grained sandstone clasts are more abundant in the Craigskelly Conglomerate. Apatites exhibit similar yellow CL colours.

Evidently oxides are lacking in the Craigskelly Conglomerate which contains more mica (MH=1%) (Craig=5%) than the Mulloch Hill Conglomerates.

The high proportion of unstable minerals in both sandstones indicates mineralogical immaturity.

Authigenic quartz overgrowths are universal and are the main cementing agent (accounting for 2%). In the Craigskelly Formation however, sparry calcite is a subsidary cement (c. 4%) developing patchily (almost resembling a poikilitic texture). Both display the effects of deformation (mild pressure solution) in the form of grain to grain contacts with straight and concavo-convex boundaries. Neither show any preferred orientation of the clasts.

6.2.2 Glenwells Shale Formation compared with the Woodland Formation

The Glenwells siltstones and the Woodland Formation siltstones (occurring at locality 206), possess mid dark-grey and pale yellow-brown coloured laminae. Both are very fine-grained with grain-size averaging approximately 0.02mm (medium silt grade) in the Glenwells Shale and 0.06mm (coarse silt grade) in the Woodland Formation, equivalent to fine silt to coarse silt grade (Fig. 6.4 and 6.5). Both are texturally immature composed of elongate to tabulate shaped, subangular-subrounded detrital grains (Fig. 6.6 and 6.7). Sorting is poorly developed with a number of larger clasts irregularly occurring in the finer-grained groundmass. The Glenwells siltstone is slightly better sorted and finer-grained, though there are some anomalously large quartz grains which do not exceed 0.06mm (coarse silt grade), whereas in the Woodland Formation the clasts are up to 1.0cm in diameter. Both siltstones are composed dominantly of calcite with a few detrital grains, mainly monocrystalline plutonic quartz, and a few grains of composite, sheared metamorphic quartz. There does appear to be slightly more feldspar in the Woodland Formation. Mineralogically the siltstones are submature.

In each black clay rich flasers are irregularly dispersed through the sediment, opaque minerals are present in small quantities and the siltstones possess a generally mottled appearance defining areas of finer-grained concentrations, attributed to the effects of bioturbation. Furthermore both are laminated. The only minor difference is the apparent lack of ostracods in the Woodland Formation.

Based upon these similarities, the Glenwells and Woodland Formation siltstones are lithologically similar.

6.2.3 Newlands Conglomerate compared with the Glenwells Burn pebbly sandstones (Craighead)

Perhaps the least immediately evident correlation is between the Newlands Conglomerates with the pebbly sandstones occurring in the Glenwells Burn (locality 98) and their mutual relationship.

Basically the Glenwells Burn pebbly sandstones (1 and 2) are similar in composition, composed of approximately 10% quartz, 30-50% lithics, very rarely feldspar (less than 1%), 5% oxides and 5% micas. The clay matrix derived in situ varies between the two with the second pebbly sandstone having almost twice as much matrix.

Colour is the most distinguishing character between the green-coloured Glenwells Burn pebbly sandstones (1) contrasting with the orange colour of Glenwells Burn pebbly sandstones (2). In addition the first conglomerate contains a more diverse assemblage of igneous rock fragments such as dolerites and trachytes, which distinguishes it from the Newlands Conglomerate.

Neither of the pebbly sandstones on first appearance resembles the Newlands Conglomerate, a matter particularly accentuated by the colour differences. Colour variation, however, may be the consequence of differential weathering. The Glenwells Burn pebbly conglomerates and sandstones are finer-grained, averaging 0.3-0.4mm (medium sand grade) in diameter, constituting medium-grained sandstone as opposed to the coarse-grained sandstones of the Newlands Conglomerate in which grains average 0.5mm (coarse sand grade) (Fig. 6.4 and 6.5) in diameter. The composition of the sandstones is basically similar in that each has approximately 10% quartz, 30-60% rock fragments and scarcely any feldspar embedded in a clay matrix (23%). Mica and oxides present in the Glenwells Burn are absent in the Newlands Conglomerate. Quartz cementation is more effective in the Newlands Conglomerate whereas secondary calcite cementation occurs only in the Glenwells Burn pebbly sandstones. Although there are slight differences in appearances, the lithostratigraphy suggests that the Newlands Conglomerate and the Glenwells Burn pebbly sandstones can be correlated.

6.2.4 Newlands Conglomerate compared with the Haven Conglomerate

The greyish-orange coloured Newlands Conglomerate contrasts petrographically with the greyish-red-purple coloured Haven conglomerate. Matrix grain size falls into the medium to coarse grade (Newlands averaging 0.5mm (coarse sand grade), Haven averaging 0.3mm (medium sand grade) in diameter). Both conglomerates are poorly sorted and grains are commonly elongate to tabulate shaped and angular to subangular (Fig. 6.6 and 6.7) bound in a matrix composed of the in situ degradation products of unstable components, which has produced a clay-rich residue. Containing almost three times more matrix (m=23%) than the Haven Conglomerate, the Newlands Conglomerate is texturally less mature than the latter. The differences are also reflected in the composition; both contain roughly the same amounts of quartz (10%), a high proportion of lithic fragments (60%) and less than 1% feldspar. Under CL, the feldspars are blue and green coloured Newlands <3% and Haven <5%. Lithic fragments include polycrystalline quartz. Unlike the Haven Conglomerate, the Newlands Conglomerate sandstones do not appear to include ripped up clasts from the underlying sediment, such as calcified siltstones, or shales, and they lack mica flakes. The Newlands Conglomerate contains yellow CL coloured apatite, whereas the Haven Conglomerate contains green CL coloured apatite. (The Haven pebbly sandstones contain up to 2% mica). Furthermore quartz cementation is the main agent in the Newlands Conglomerate whilst calcite is more effective in the Haven sandstones.

6.2.5 Upper Saugh Hill Grits Formation compared with the Scart Grits Formation

The Upper Saugh Hill Grits and the Scart Grits have rather similar colours, the former possesses a dappled pale yellow-brown colour whilst the lower member of the Scart Grits is a light- to pale-brown colour.

Both of the sandstones are poorly sorted. Grain-size ranges are 0.2-2.0mm (sand grade) in diameter for the Upper Saugh Hill Grits and 0.2-0.4mm in the Scart Girts, i.e fine to very coarse (Fig. 6.6 & 6.7). The low sphericity of matrix grains, the angular to subangular clasts, and low abundance of matrix (13%) in the Upper Saugh Hill Grits, matches that of the Scart Grits (c. 8%) and consequently the textural maturity of the sediment is low. Correspondingly the matrix consits of clay material accumulating between pockets.

Mineralogically the sandstones are also immature, composed of a high percentage of lithic fragments (USH=66%), (Scart=53%) namely polycrystalline quartz, dolerite, chert, mica, schistose quartz. Quartz occurs in roughly the same proportions (USH=9%) (Scart=11%), as do micas (USH=9%) (Scart=7%), whilst feldspars, mainly twinned plagioclase, are scarce (less than 1%) distinctively luminescing blue and green under CL. Similarly the apatite luminesces green.

In both instances the sediments are bound together by authigenic quartz overgrowths and by the effects of pressure solution occurring at grain contacts, precipitating a siliceous cement. Additionally secondary calcite cementation occurs irregularly in small patches but is more effective and abundant in the Scart sandstones.

Texturally and mineralogically the sandstones resemble each other. There are, however, a few dissimilarities. At the base of the Upper Saugh Hill Grits there is a basal sugar-quartz pebbly sandstone in which the dominant pebbles are composed of polycrystalline quartz, yet at Woodland Point the pebbly sandstones occurring near the base of the Scart Grits exposures contain a more diverse composition of lithic fragments including quartz, dolomite, igneous clasts and intraformational clasts. The latter originate from the Woodland Formation. These clasts are much larger; up to 5-15cm in diameter. Occasionally there are some horizons in which the small pebbles are almost exclusively composed of quartz. Finally under CL, brachiopod valves and crinoid ossicles are present in the Scart Grits, but no fossil fragments were found during this investigation in the Saugh Hill Grits (though some were reported by Freshney (1959)).

These apparent differences may be the result of poor exposure in the Craighead Inlier, though primarily they are attributed to local variations during deposition of the sediments, and to composition of the source lithology, rate of supply and different depositional environments.

6.3 DISCUSSION

Petrographically the Craighead Inlier and coastal sediments cannot be satisfactorily correlated. There are variations between them in grain-size, colour and composition of the Formations. It is probable that the two successions were deposited in separate areas of sediment accumulation sharing a universal source area. The Mulloch Hill Conglomerates were deposited first and whilst these conglomerates were accumulating, the Craigskelly Conglomerates started to be rapidly dumped in a fan system. Initially the source area provided an abundant supply of volcanic and low-grade metamorphic rocks and granites. Overall immaturity of the sediments indicates that the clasts have not travelled far. Slight differences especially in the composition of the pebbles in the conglomerates and grains in the sandstone may be related to local variations such as 1) composition of the local source area and the availability of the minerals 2) and rate of supply of detritus.

In the discussion following the presentation of their paper, Cocks and Toghill (1973) were asked by Ingham why they had given separate names to the Glenwells Shale unit, Woodland Formation and Tralorg Formation, when they appeared to be a single formation (dominantly argillaceous with a locally developed calcarenite). The authors replied that despite a correlation using graptolites the character of the rocks in the three areas are somewhat different and that these differences would be masked if a common name was used. Since it is apparent that the sediment accumulated in separate areas, and following Cocks and Toghill, the individual formation names have been retained here.

Combined with transmitted light CL improves the quantity and quality of geological information. Unfortunately, the limited time dictated that only a preliminary study of the sediments of the Craighead and Girvan shore could be undertaken. More detailed work for future researchers will provide important data on accurate estimates of the mineral constituents, which in itself will give more information on both the provenance and the diagenesis and structural deformation history of the sediments.

Plates 4.1 - 4.8 (Chapter 6)

Plate 4.1

CRAIGSKELLY CONGLOMERATE FORMATION

Figure

1. Poorly sorted, clast supported, pebbly sandstone. On the top right there is a volcanic rock fragment.
TW.204.166. Scale: bar represents 1 mm, *PPL*.

2. Under crossed nicols, the volcanic rock fragment consists of plagioclase laths set in an altered groundmass which is too fine-grained to be identified. Calcite cement is patchily developed as seen in the bottom right hand corner.
TW.204.166. Scale: bar represents 1 mm, *XPL*.

3. Poorly sorted, coarse-grained lithic arenite. The quartz clast (centre right), contains small inclusions. Quartz cementation occurs at grain boundaries.
TW.204.167. Scale: bar represents 0.5 mm, *XPL*.

4. Poorly sorted, coarse-grained lithic arenite, containing another quartz grain (top left) with small inclusions. The dark coloured clast (centre right) is composed of lenticular laths of plagioclase.
TW.204.168. Scale: bar represents 1 mm, *XPL*.

5. A thin vein composed of calcite, occurring in a poorly sorted coarse-grained lithic arenite.
TW.204.169. Scale: bar represents 1 mm, *XPL*.

6. Another vein composed of calcite in which the various calcite plates can be seen. A plagioclase feldspar clast is differentiated from quartz by the lamellae twinning.
TW.204.167. Scale: bar represents 1 mm, *XPL*.

7. Poorly sorted, pebbly sandstone. On the right hand side there is a large siltstone clast through which a thin vein passes, composed of quartz.
TW.204.170. Scale: bar represents 1 mm, *XPL*.

8. Large monocrystalline quartz clasts containing a number of thread-like fractures and veins of calcite. The surrounding matrix is composed of clay minerals, namely kaolinite derived from the in situ degradation of the clasts.
TW.204.170. Scale: bar represents 1 mm, *XPL*.

PLATE 4.1

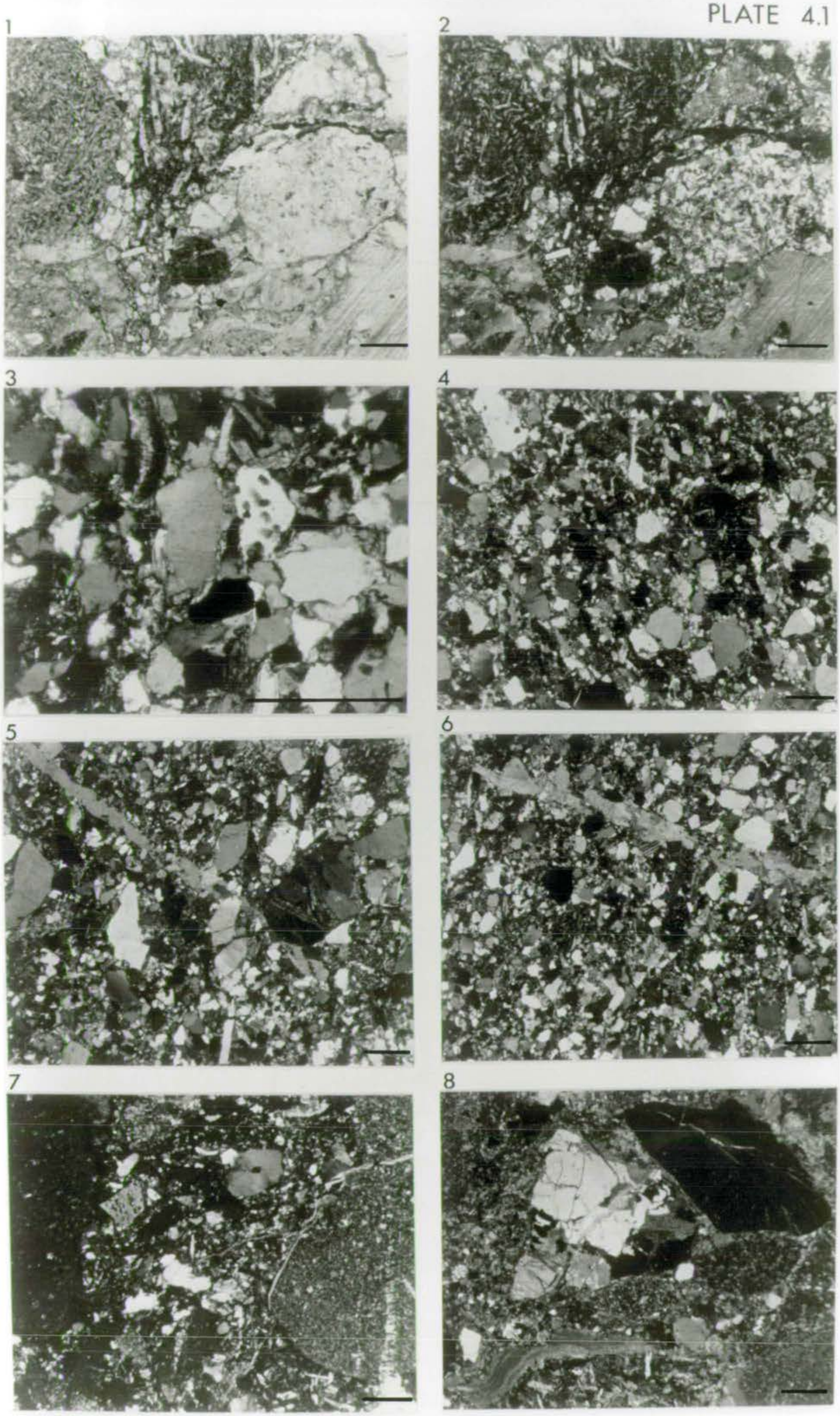


Plate 4.2

WOODLAND FORMATION

Figure

1. Poorly sorted breccia occurring at the base of the Woodland Formation. The breccia is matrix supported, and clast composition includes quartz chert.
TW.206.171. Scale: bar represents 1 mm, *XPL*.

2. Calcareous cemented granular sandstone. Calcite is patchily distributed, and occasionally produces a poikilitic texture where one coarse cement crystal envelopes many detrital grains.
TW.206.173. Scale: bar represents 1 mm, *XPL*.

3. Poorly sorted fine-grained siltstone. The slightly larger grains tend to be composed of monocrystalline quartz. The general mottled appearance is due to bioturbation. Cutting across the left hand corner is a thin vein infilled with calcite.
TW.206.173. Scale: bar represents 1 mm, *XPL*.

4. Bioclastic mudstone. The circular shaped, single calcite crystals having a general dusty appearance are crinoid ossicles. The disarticulated brachiopod valve (upper left-hand corner) exhibits a clear fibrous structure.
TW.232.174. Scale: bar represents 0.5 mm, *XPL*.

5. Laminated siltstone. The bioclastic, poorly-sorted siltstone grades up into a poorly sorted shale. A rugose coral occurs centre right. The contact between the shale and the overlying coarser-grained siltstone is sharp.
TW.232.174. Scale: bar represents 0.5 mm, *XPL*.

6. Laminated siltstone, occurring in the upper part of the Woodland Formation. The lighter coloured coarse grained band, overlying the darker mudstone band, is more quartz rich and is seen to be gently loading into the mudstone.
TW.216.175. Scale: bar represents 1 mm, *XPL*.

7. Laminations in a siltstone are displayed by a fracture which is infilled with speckled calcite. The general mottled appearance of the dark coloured mudstone (base) is due to bioturbation.
TW.216.176. Scale: bar represents 1 mm, *XPL*.

PLATE 4.2

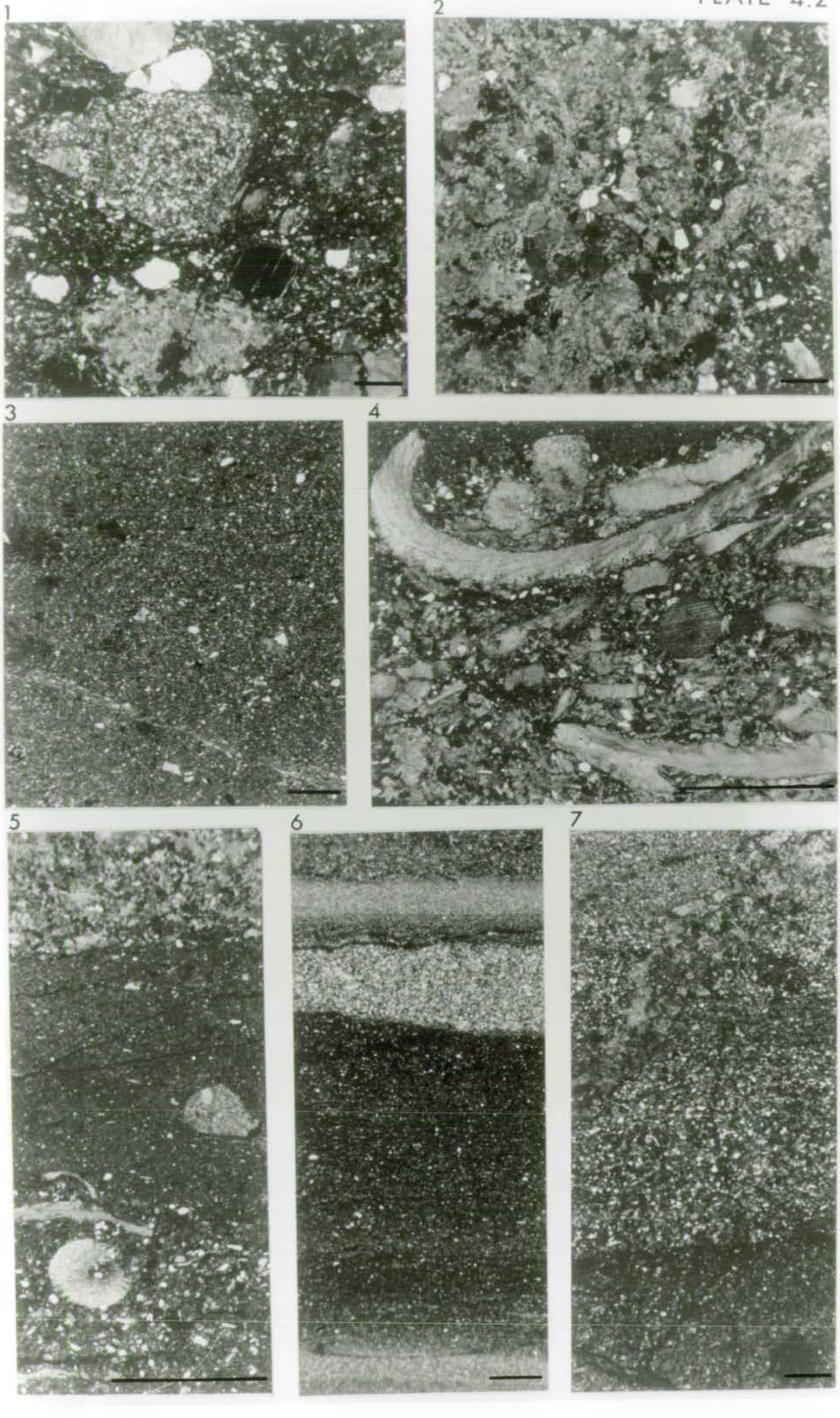


Plate 4.3

HAVEN CONGLOMERATE

Figure

1. Poorly sorted lithic arenite. Monocrystalline quartz appears dominant, and one large grain (top right) contains similar inclusions as found in the Craigskelly Conglomerate, Plate 4.1.
   TW.218.177. Scale: bar represents 1 mm, *XPL*.

2. Poorly sorted granular sandstone. Quartz is dominant. The boundaries between the crystals in the large polycrystalline quartz grain are sutured.
   TW.218.178. Scale: bar represents 1 mm, *XPL*.

3. Close up, in which grains are found floating in calcite. As a result of the calcite corroding the grains, some of the quartz grains display secondary angularity.
   TW.218.178. Scale: bar represents 0.5 mm, *XPL*.

4. Grains almost exclusively composed of monocrystalline and polycrystalline quartz. The long dark grain (base, right) is a laminated siltstone.
   TW.218.178. Scale: bar represents 1 mm, *XPL*.

5. Poorly sorted coarse-grained sandstone. The large dark grain on the right is a siltstone. Some of the grains are seen partially disintegrating, producing matrix.
   TW.218.179. Scale: bar represents 1 mm, *XPL*.

6. A large monocrystalline quartz grain containing tiny vacuoles concentrated into faint lines and small inclusions, is surrounded by smaller quartz grains which are protruding into the large grain.
   TW.218.180. Scale: bar represents 0.5 mm, *XPL*.

7. Fining upwards sequence displayed in a quartz rich coarse-grained sandstone. Towards the top there are long muscovite mica flakes which show a preferred orientation parallel to bedding.
   TW.218.180. Scale: bar represents 1 mm, *XPL*.

PLATE 4.3

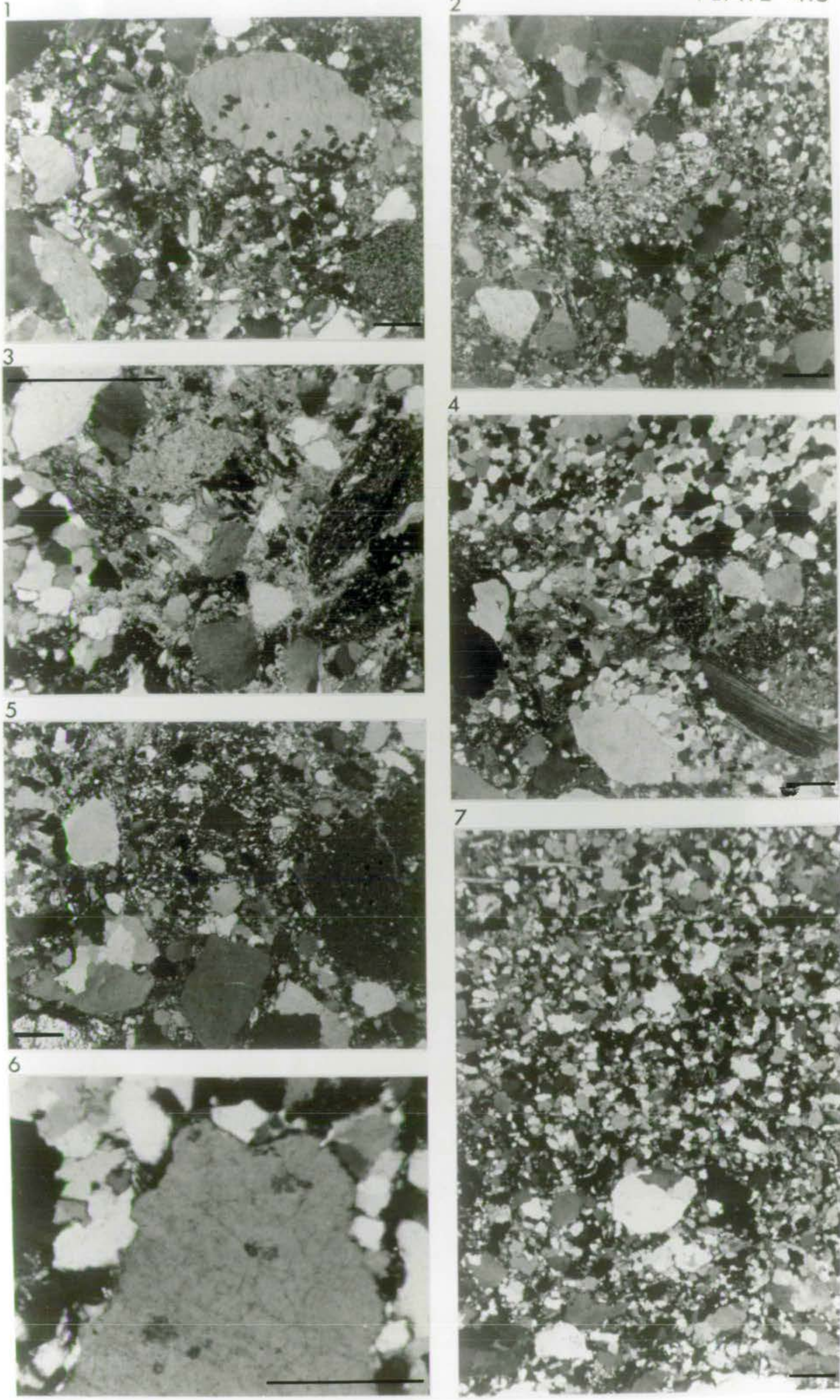


Plate 4.4

SCART GRIT FORMATION

Figure

1. Poorly sorted coarse-grained lithic arenite.
   TW.226.181. Scale: bar represents 1 mm, *PPL*.

2. Same section under crossed nicols. The lithic arenite is poorly sorted, composed of monocrystalline quartz and rock fragments. Feldspars are scarce.
   TW.226.187. Scale: bar represents 1 mm, *XPL*.

3. The large grain on the left is possibly a chert grain, whilst the large grain on the right is a poorly sorted coarse-grained sandstone, containing large monocrystalline quartz grains.
   TW.226.182. Scale: bar represents 1 mm, *XPL*.

4. Poorly sorted coarse-grained lithic arenite.
   TW.225.183. Scale: bar represents 1 mm, *XPL*.

5. Towards the top of the Scart Grits, there is a pebbly sandstone horizon. The grains are of low sphericity, angular to subrounded, and poorly sorted.
   TW.226.184. Scale: bar represents 1 mm, *XPL*.

6. Small plagioclase grain in which the parallel twinning is offset by a small fracture. The matrix is derived from the degradation of the component grains.
   TW.226.184. Scale: bar represents 0.5 mm, *XPL*.

PLATE 4.4

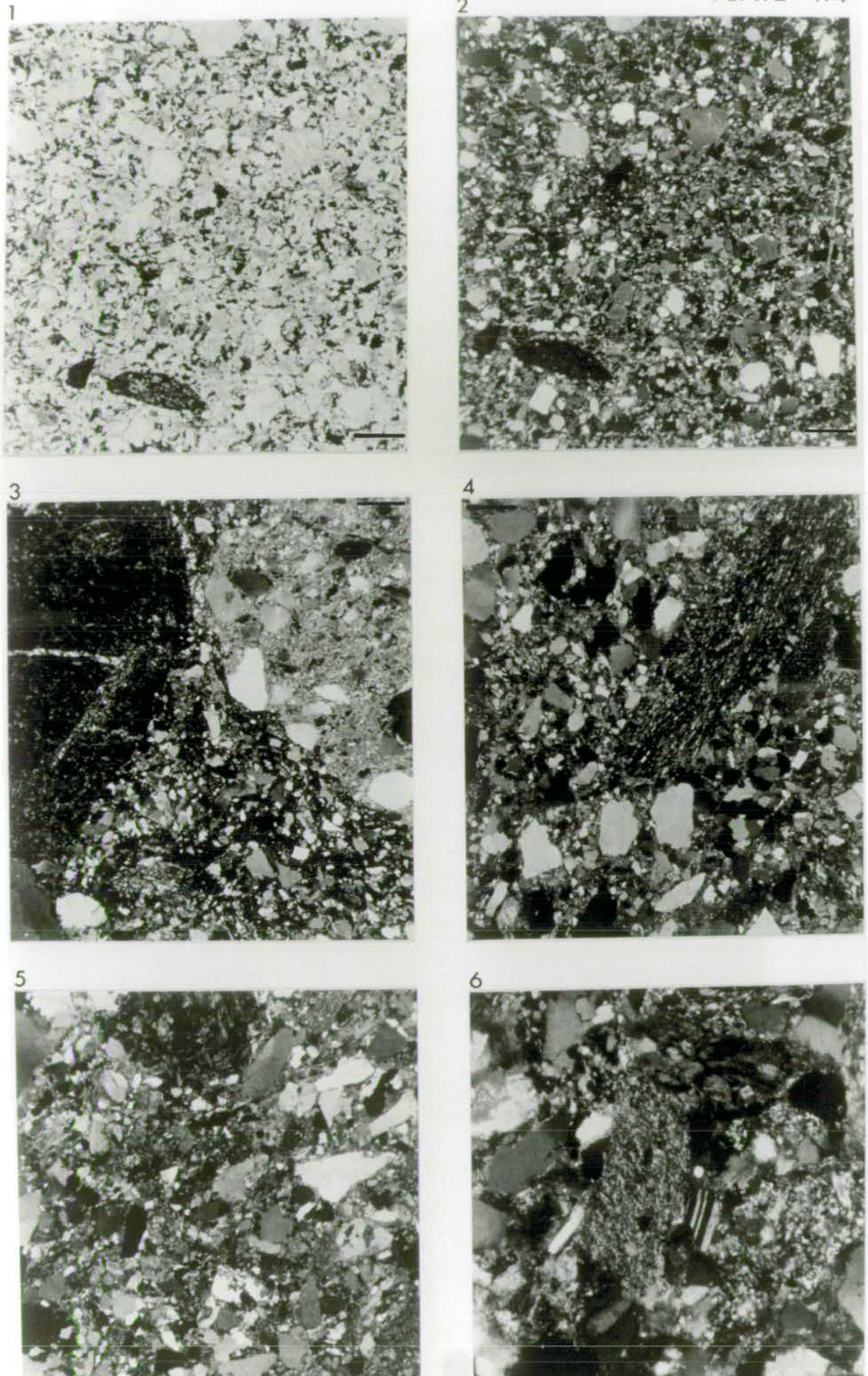


Plate 4.5

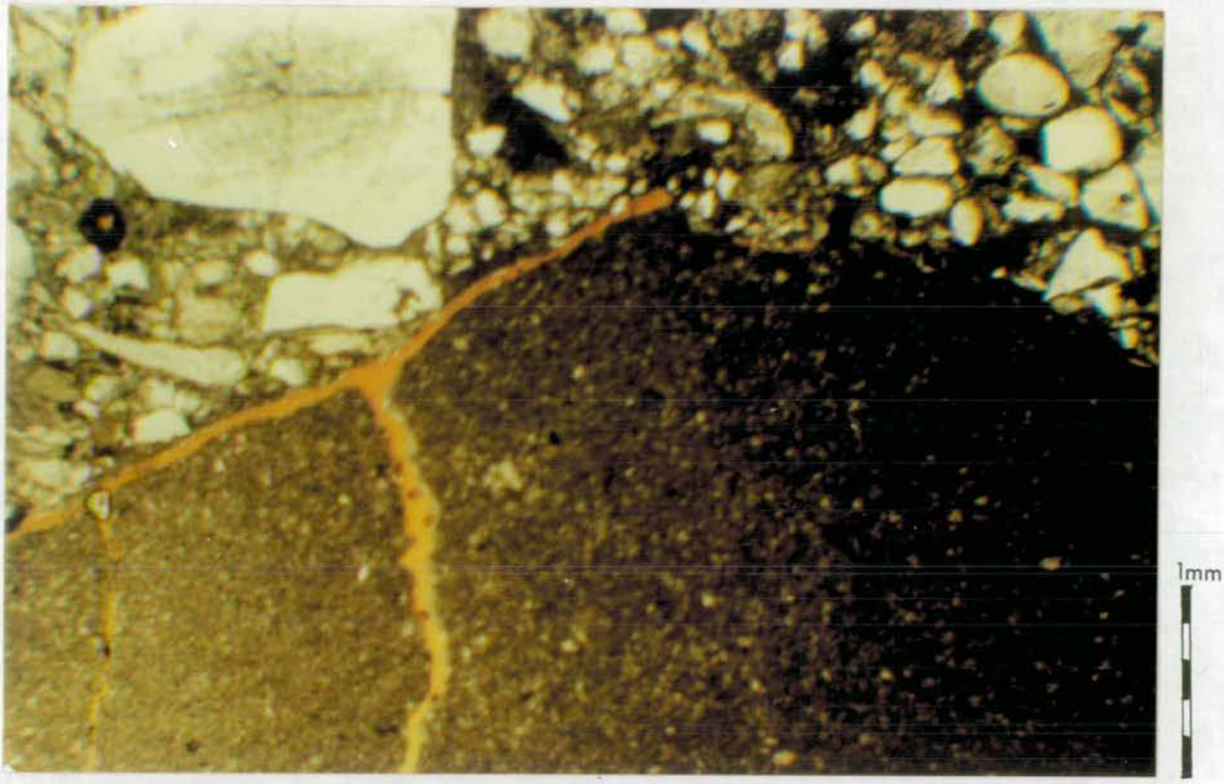
CRAIGSKELLY CONGLOMERATE FORMATION

Figure

1. Poorly-sorted pebbly sandstone.
TW.204.191. Scale: bar represents 1 mm, *Tr.L.*

2. The large lithic clast in the fore-ground is composed of a feldspar-rich siltstone, in which the feldspars luminesce pale blue and red. The pale green thin rim coating the edge and cutting into the pebble is Araldite mounting medium. Other components include purple- and brown-luminescing quartz, blue-luminescing feldspars, and green-luminescing apatite. Most of the quartz is distinctly brownish, suggesting a dominantly metamorphic provenance.
TW.204.191. Scale: bar represents 1 mm, *Tr.L.*

1



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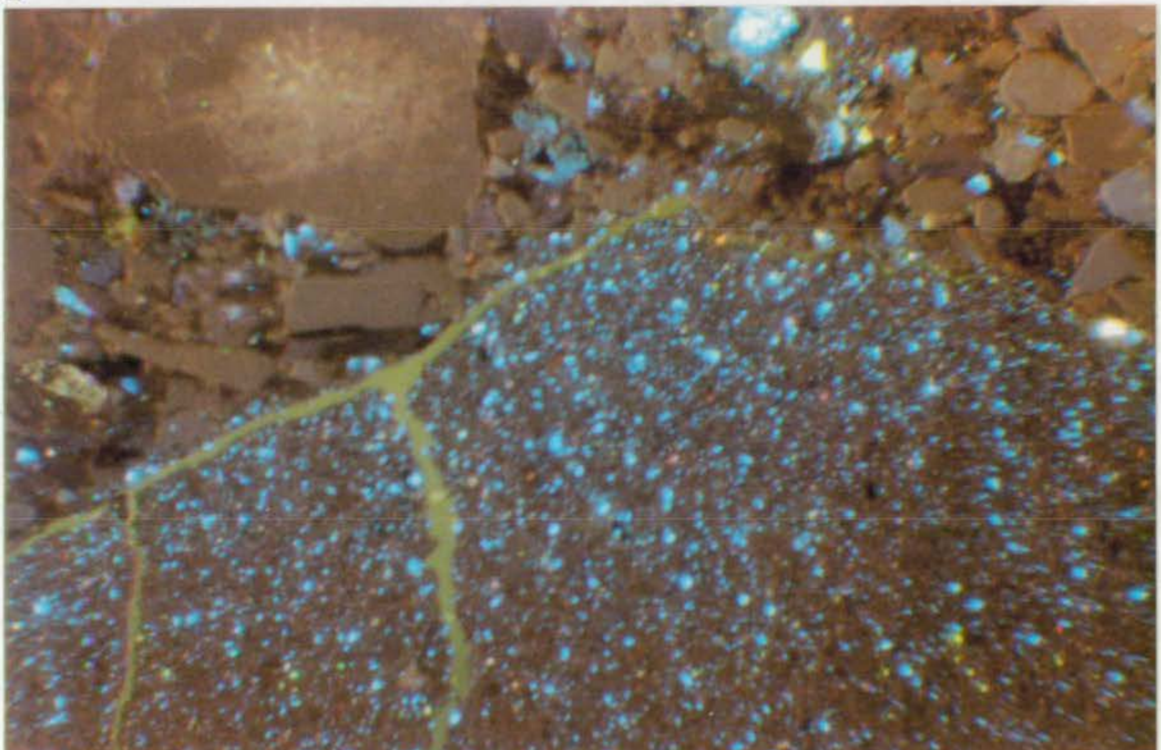


Plate 4.6

WOODLAND FORMATION

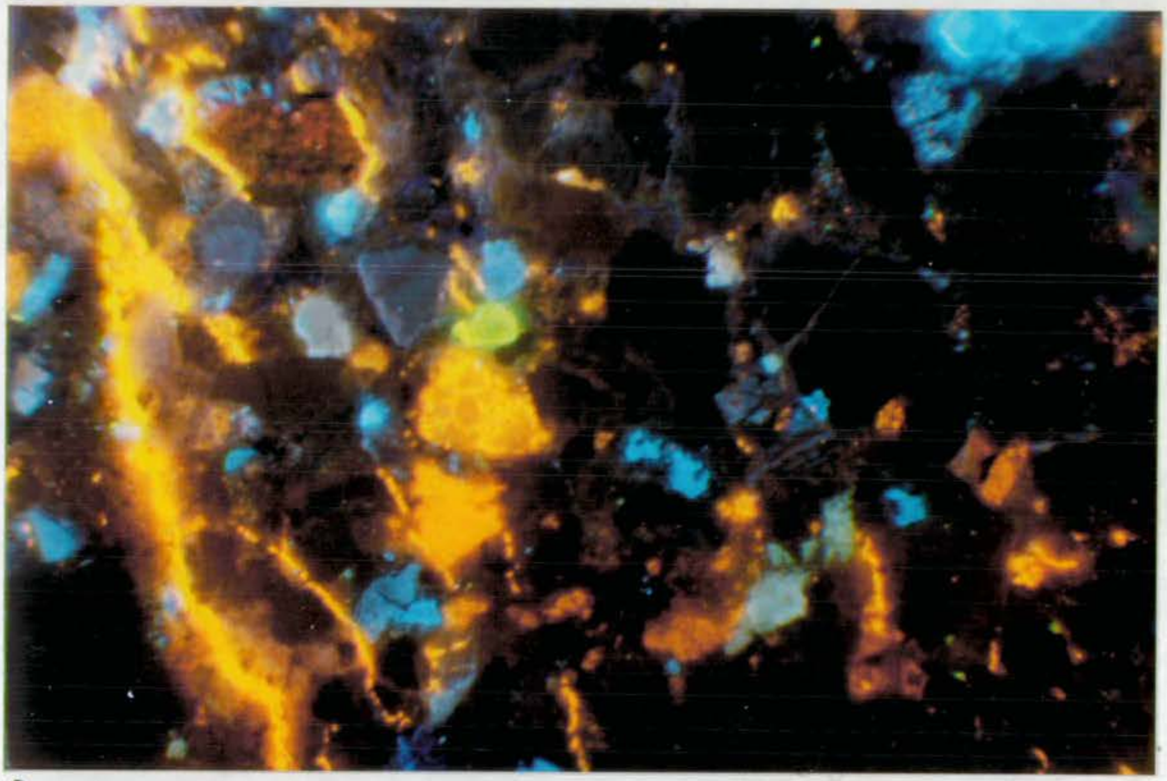
Figure

1. Coarse-grained sandstone.
   TW.214.192. Scale: bar represents 1 mm, *Tr.L.*

2. The feldspars are fairly abundant and luminesce a deeper blue colour than the feldspars occurring in the underlying Craigskelly Conglomerate. Rock fragments are also present; for example the red grain in the upper right corner, as well as quartz. Some of the feldspar is being hydrothermally altered into kaolinite. Characteristically, apatite luminesces a yellow-green colour. Extensive yellow calcite veining is also present.
   TW.214.192. Scale: bar represents 1 mm, *CL.*

1

2



1mm

3

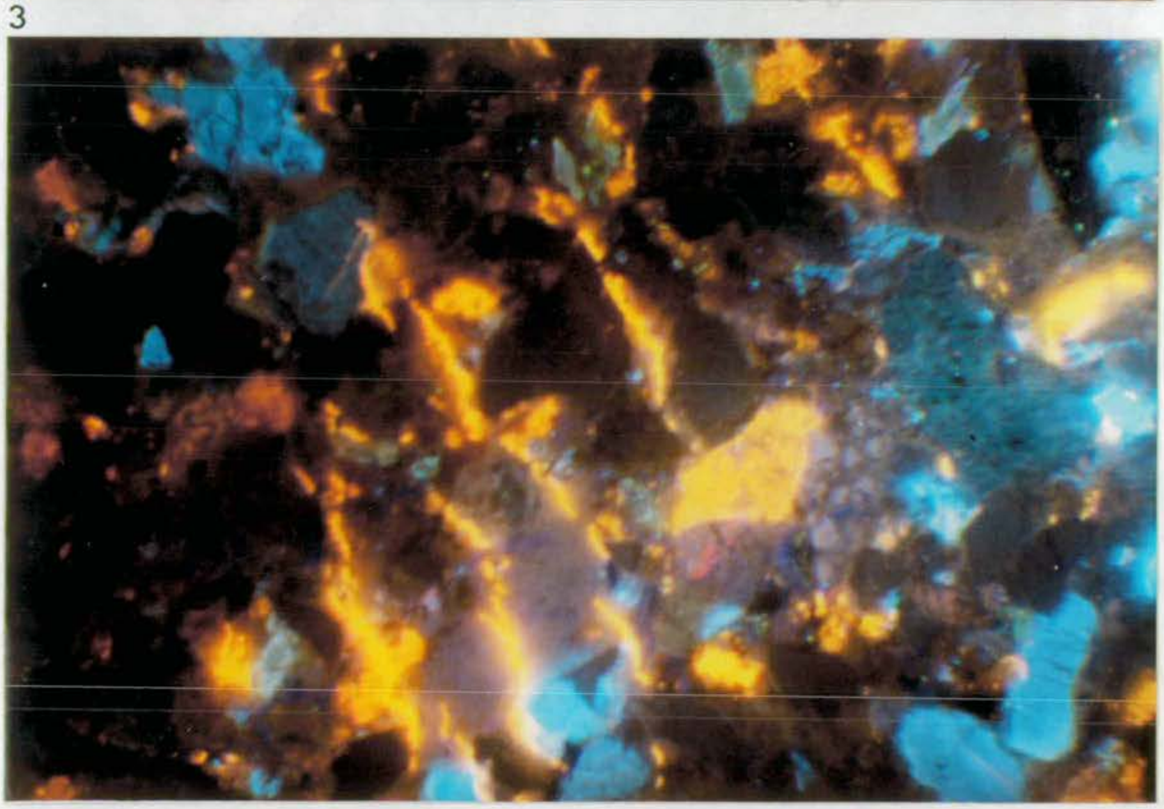


Plate 4.7

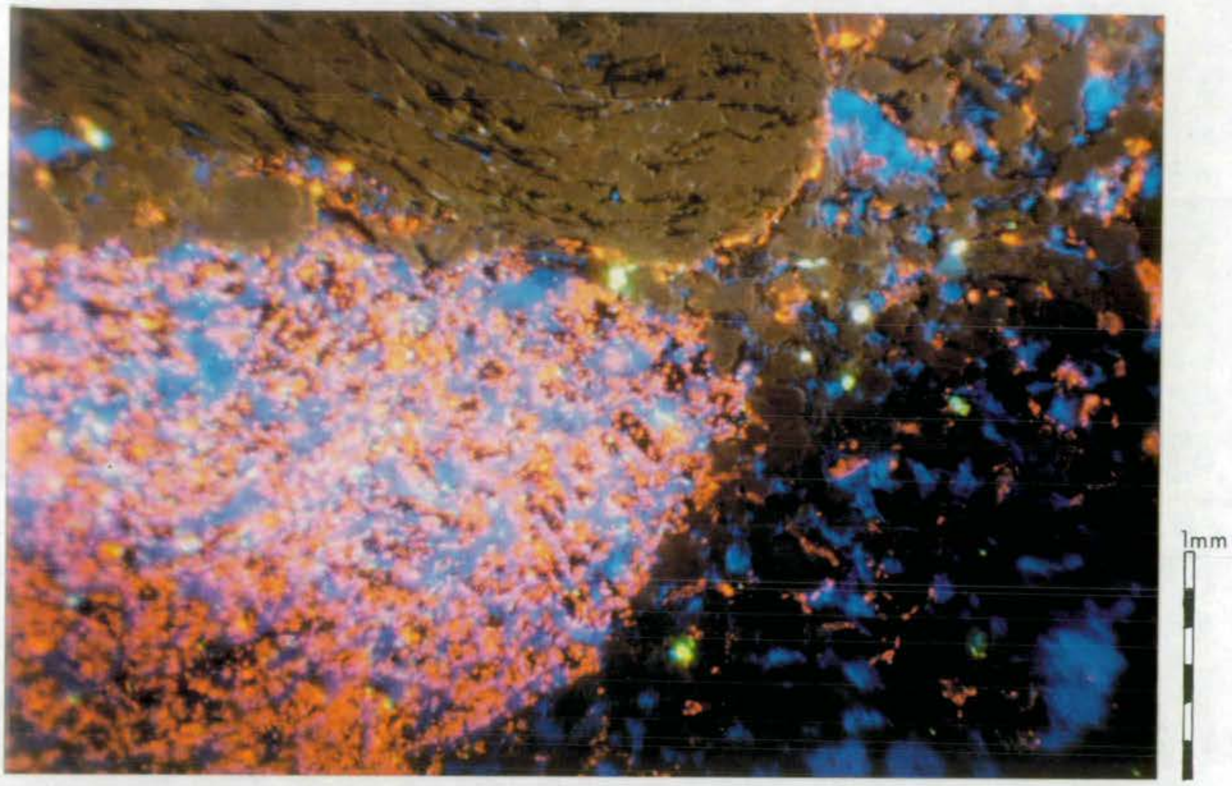
HAVEN CONGLOMERATE

Figure

1. The large brown-luminescing pebble in the upper region is composed of quartz, feldspar and ?micas showing schistosity and clearly of metamorphic origin. The red and blue pebble below is probably an altered igneous pebble, with non-luminescent ferromagnesian minerals being replaced by calcite, with a blue reticulum of feldspar crystals. Apatite grains luminesce yellow-green. In the lower right-hand corner, the deep blue colour represents a kaolinite/dickite cement in the matrix.
   TW.218.194. Scale: bar represents 1 mm, *CL*.

2. Close-up of the altered igneous clast from above, showing the lighter blue feldspar crystals surrounded with an alteration halo of kaolinite/dickite. Note the compression fractures in the large quartz pebble at the bottom, annealed by both calcite and kaolinite cements.
   TW.218.194. Scale: bar represents 1 mm, *CL*.

1



2

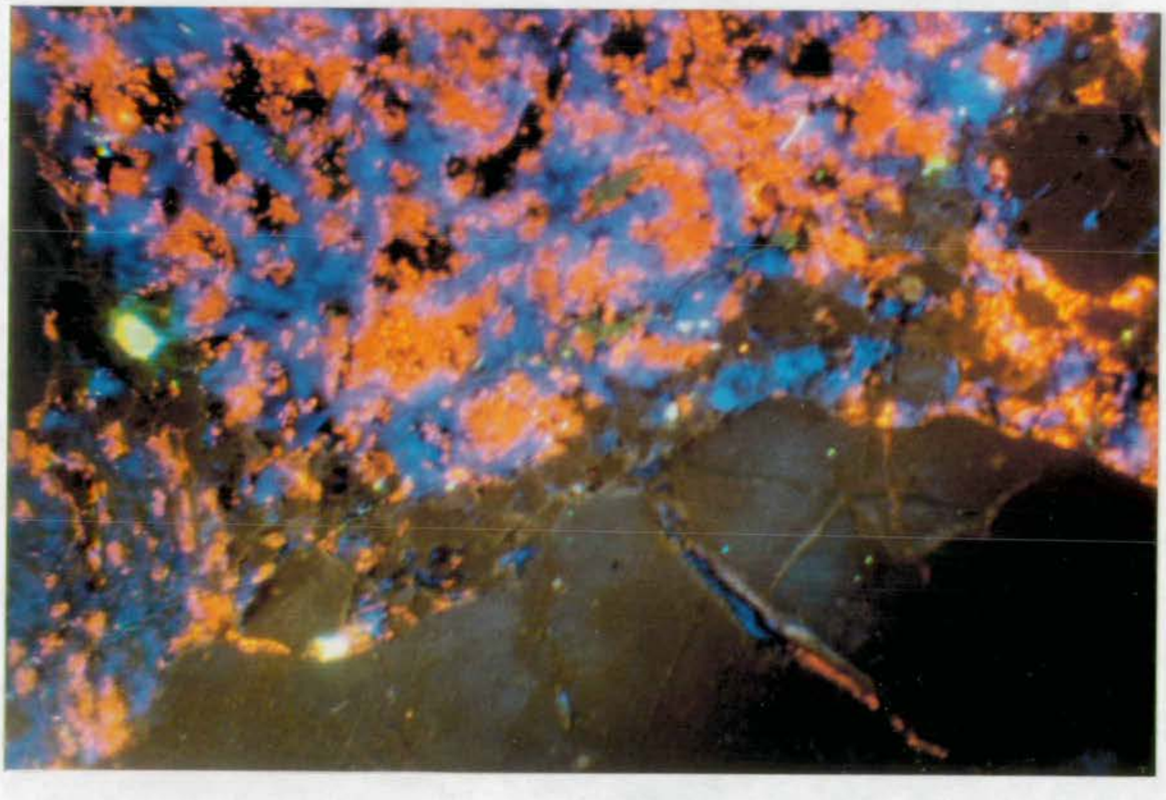


Plate 4.8

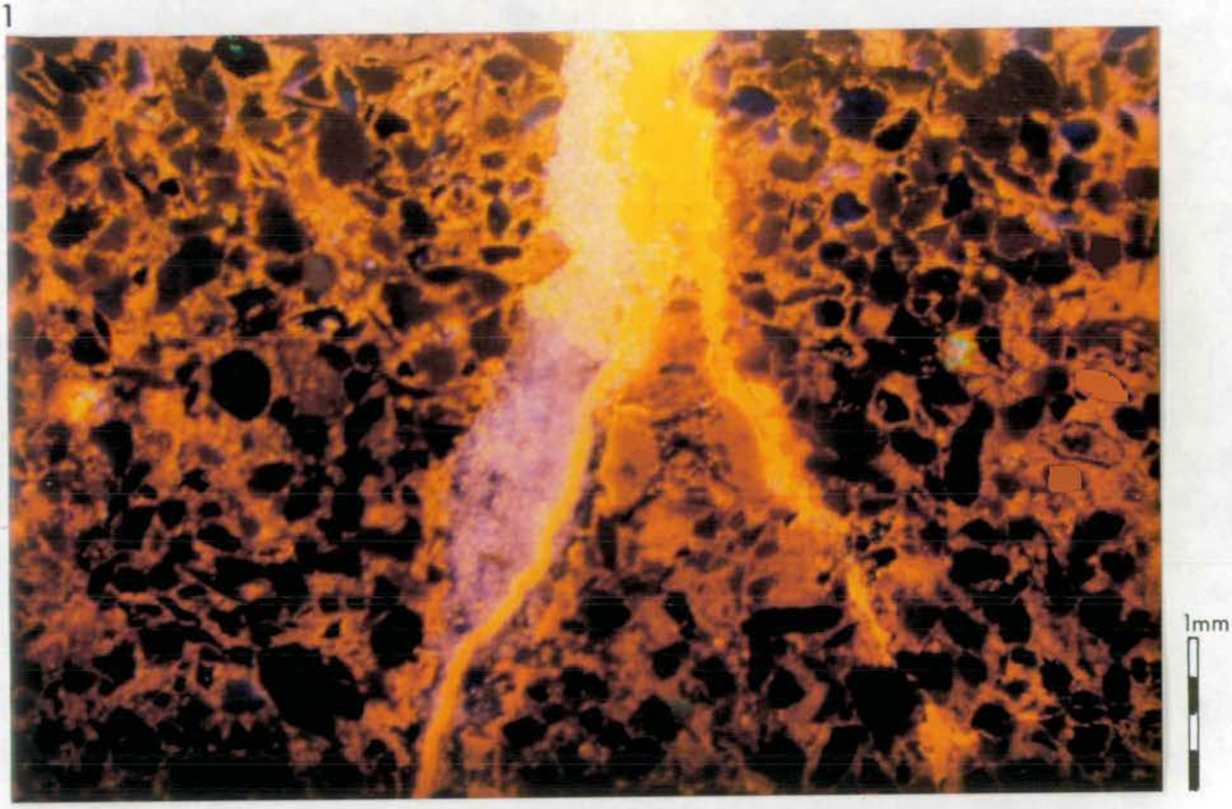
SCART GRIT FORMATION

Figure

1. Calcarous cemented poorly-sorted medium-grained sandstone. Quartz and feldspar grains display secondary angularity, as a consequence of the calcite dissolving and replacing the grains. The large vein is infilled by a later brighter-yellow phase of calcite.
   TW.226.195. Scale: bar represents 1 mm, *CL*.

2. The curved fragments in the centre field of view which are composed of calcite are probably cement-filled moulds of brachiopod fragments. The bright yellow-green luminescing grains are composed of apatite. Blue grains are feldspars altered to kaolinite/dickite.
   TW.226.195. Scale: bar represents 1 mm, *CL*.

1



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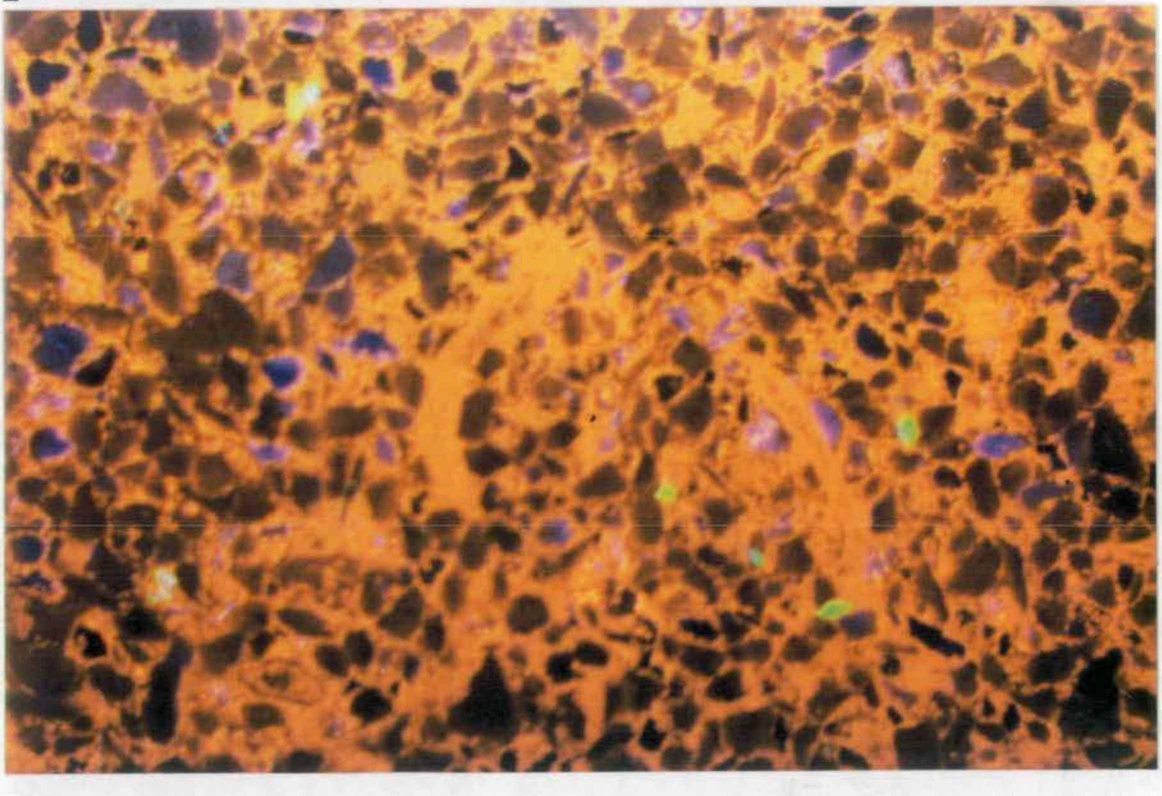


CHAPTER 7

7. THE BIOSTRATIGRAPHY AND TAPHONOMY OF THE CRAIGHEAD INLIER AND COASTAL SECTION

7.1 THE BIOSTRATIGRAPHY OF THE CRAIGHEAD INLIER

Constituting the most fossiliferous unit in the Craighead Inlier, the Mulloch Hill Group provides a rich and diverse fauna, which gradually changes in composition through the succession.

7.1.1 Mulloch Hill Conglomerate Formation

The only fauna found in this formation was recovered from the middle, thinly bedded, medium-grained lithic sandstone member of the Mulloch Hill Conglomerate (locality 1). Fossils tended to be distributed in specific horizons as opposed to being scattered indiscriminately through the lithology.

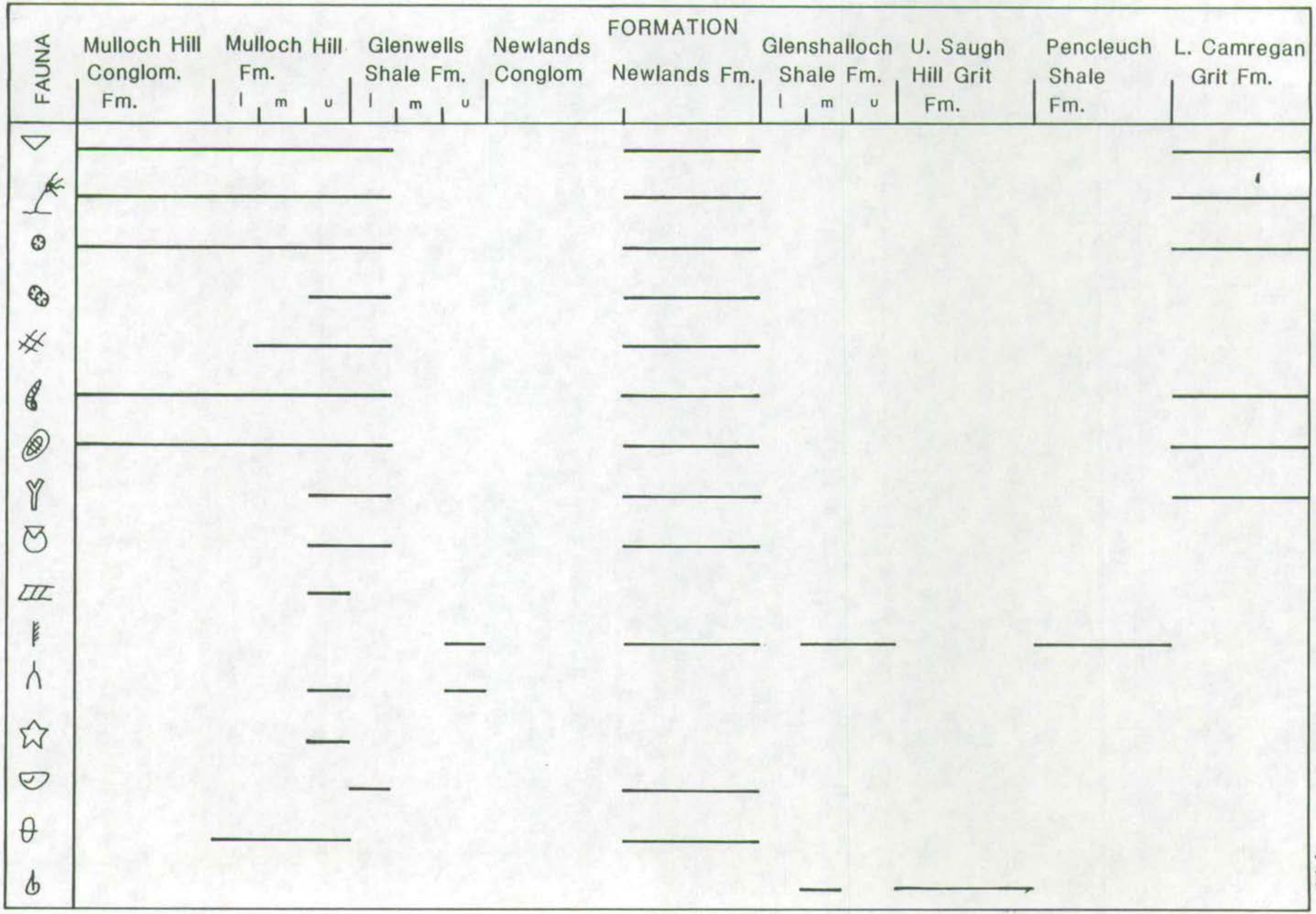
The fauna is of low diversity and fossils obtained are mainly brachiopods having affinities with the underlying Ordovician High Mains Sandstone (Harper, 1988), as discussed in greater detail at the end of Chapter 8. Of the six species identified (Ward, P.M. 1989; Cocks & Toghill, 1973), *Hyattidina ? angustifrons* (Salter) is dominant; the other taxa present are *Lingula*, *Fardenia*, and *Leptaena*, with dalmanellids and, rhynchonellids. Normally these forms are characteristic of shallow shelf conditions.

As well as brachiopods, there are abundant loose crinoid ossicles and Cocks (pers comm) has reported rare gastropod and trilobite specimens (Fig. 7.1). Apart from *Hyattidina* which is ususally found intact the brachiopods are disarticulated and are occasionally fragmented.

7.1.2 Mulloch Hill Formation

Within the Mulloch Hill Formation, there is a gradual increase in faunal diversity (Fig. 7.1 & 2). The fossils are concentrated in specific horizons, located near the bases and/or tops of the individual beds. Some fossil horizons extend for over a metre and may be up to 8cm thick.

Algal fragments are also minor constituents. Originally the Mulloch Hill forms were described as *Mastopora fava* (Currie and Edwards, 1942) (the genus *Mastopora* designated by Eichwald, 1840) but later they were re-assigned as *Cyclocrinites favus* (Nitecki, 1970). They are only very rarely preserved intact and are more commonly found as flattened external or internal mould fragments



Fig(7.1) Stratigraphical distribution of the fossils in the Craighead Inlier.

Figure 7.2 Fossils in the Mulloch Hill Formation

Cyclocrinites favus (Nictecki)
Rhagmophyllum crenulatus (McCoy)
Heliolites sp.
Ptilodictyne cryptostomes? stictopora

Pectocrania mullochensis (Reed)
Schizonema subplicatum (Reed)
Mendacella mullockiensis (Davidson)
Dictyonella sp.
Eostropheodonta mullochensis (Reed)
Fardenia (Fardenia) columbana (Reed)
Stricklandia lens mullochensis (Reed
Rhynchotreta cuneata (Dalman)
Rostricellula mullochensis (Reed)
Hyattidina angustifrons (Salter)
Zygospiraella scotica (Salter)

bivalve fragments
Loxonema sp.
Lophospira sedgwickii
Kohenospira sp.
Murchisoniacean sp.
*Murchisoni*a sp.
?*Phanerotrema* sp.
Trochonema sp.
Orthoceras sp.
Hyolithes sp. ind. (B)
Petalocrinus sp.

Faillaena maccaulumi (Salter)
Stenopareia thomsoni (Salter)
Cyphoproetus externus (Reed)
Astroproetus scoticus (Reed)
Hadromeros elongatus (Reed)
Encrinurus squarrosus Howells
Calymene sl. *ubiquitosa* Howells

Rough Neuk Starfish Bed
Ptilodictyne cryptostomes
Asteroidea
disparid inadunate crinoid

Dictyonema areyi (Gurley)

Acernaspis cf . *elliptifrons* (Esmark)
Lichas silvestris (Reed)
Dicranopeltis sp.
Platylichas scoticus (Reed)
Hemiarges sp.
Hemiarges serus (Reed)
Leonaspis cf. *L. deflexa* (Lake)
Leonaspis sp.
Anacaenaspis callipareos (Thomson)

consisting of rounded and closely packed hexagonal 'prominences' (domes or depressions) with a honeycomb appearance (Plate 7.1.1 and 2). A central papilla represents the cast of the pore. Since most calcareous algae disintegrate after death, it is possible that the fragments of cyclocrinitids were subject to some degree of post-mortal transportation (Riding, 1975) or were reworked prior to burial. Sponges are also present (Plate 7.1.4 and 5).

The solitary corals are monospecific, identified as *Rhagmophyllum crenulatus* (McCoy), Plate 7.1.3). Distinguished by its disc-like axial boss, this form is very common in the Ordovician. Tabulate corals such as *Heliolites* are rare (Plate 7.1.6). Characteristically the cylindrical corallites are separated from each other.

Numerically less important, the bryozoans are likely to be of a single species. They are ptilodictine cryptostomes, which are characterised by erect branching colonies with tubular shaped zooecia (Plate 7.2.1 & 2). The fronds are flat and have a bilamellate construction in which the zooecia arise from the both sides of a median lamina.

Throughout the formation brachiopods are dominant. During this investigation twelve species have been identified, indicating that there was an increase in brachiopod species diversity from the underlying Mulloch Hill Conglomerate to Mulloch Hill Formation (Fig. 7.2). Numerically *Hyattidina*? *angustifrons* (Salter) is dominant. *Mendacella mullockiensis* (Davidson), *Zygospiraella scotica* (Salter), *Rhynchotreta cuneata* (Dalman), *Resserella canalis* (J de C Sowerby), *Isorthis amplificata* (Walmsley) *and Fardenia columbana* (Reed) are all major constituents of the assemblage. A taxonomic review of the brachiopods from the Mulloch Hill Formation is given in Chapter 8. Cocks and Toghill (1973) state that towards the top of the formation, above Rough Neuk Quarry (locality 89) there is a distinct change in the brachiopod species. From the gully below Kirk Hill (NS 27030445) they collected nine different brachiopod species dominated by *Leangella scissa* (Davidson), but other species included *Mendacella mullockiensis* (Davidson), *Dolerorthis* sp., *Eoplectodonta duplicata* (J de C Sowerby), *Meifoida* sp.. During this investigation this locality was not found but a similar fauna was collected from the same gully (locality 52 and 54), in the Glenwells Shale Formation.

In Rough Neuk, fragments of cephalopods and bivalves are present. Unfortunately the specimens are very poorly preserved - possibly the cephalopod belongs to the species *Orthoceras* (Plate 7.2.3-5). Hind's (1910) monograph of the lamellibranchs (bivalves) of Girvan, figures all the species present.

In addition a few *Hyolithe*s specimens were found (Plate 7.2.6). Although there are some extensive fossil horizons traced for up to 0.50cm in Rough Neuk Quarry the fossils are generally scattered throughout the lithology.

Likewise the gastropod fauna is moderately diverse. Seven species of gastropods were identified, dominated by the conically shelled, high spired *Loxonema* sp, and *Lophospira sedgwicki*, with additional specimens of ?*Phanerotrema* sp., *Kohenospira* sp., murchisoniacean indet., *Trochonema* sp., and *Murchisonia* sp. (Plate 7.3). *Phragmostoma decipians, Liospira marklandensis* were also examined in the Sedgwick Museum, Cambridge (Fig. 7.3).

Clusters of disassociated crinoid columnals are abundant throughout the Mulloch Hill Formation. None of these are distinctive enough to be assigned to a particular species, though this may become possible in the future (e.g. Donovan, 1988). It appears that there are two species present - one which may be an artificial morphotaxon (Plate 7.7). A single arm of *Petalocrinus* sp. fragment was also found; a triangular blade possessing a dendritic branching pattern with the ambulacral grooves marking the former existence of the branching arms (Plate 7.7.1).

The trilobite assemblage is diverse - up to seventeen species have been described by Howells (1982) (Fig. 7.2). *Calymene* s.l. *ubiquitosus* Howells, *Encrinurus squarrosus* Howells *Acernaspis* cf. *elliptifrons* (Esmark) are common forms (Plate 7.8).

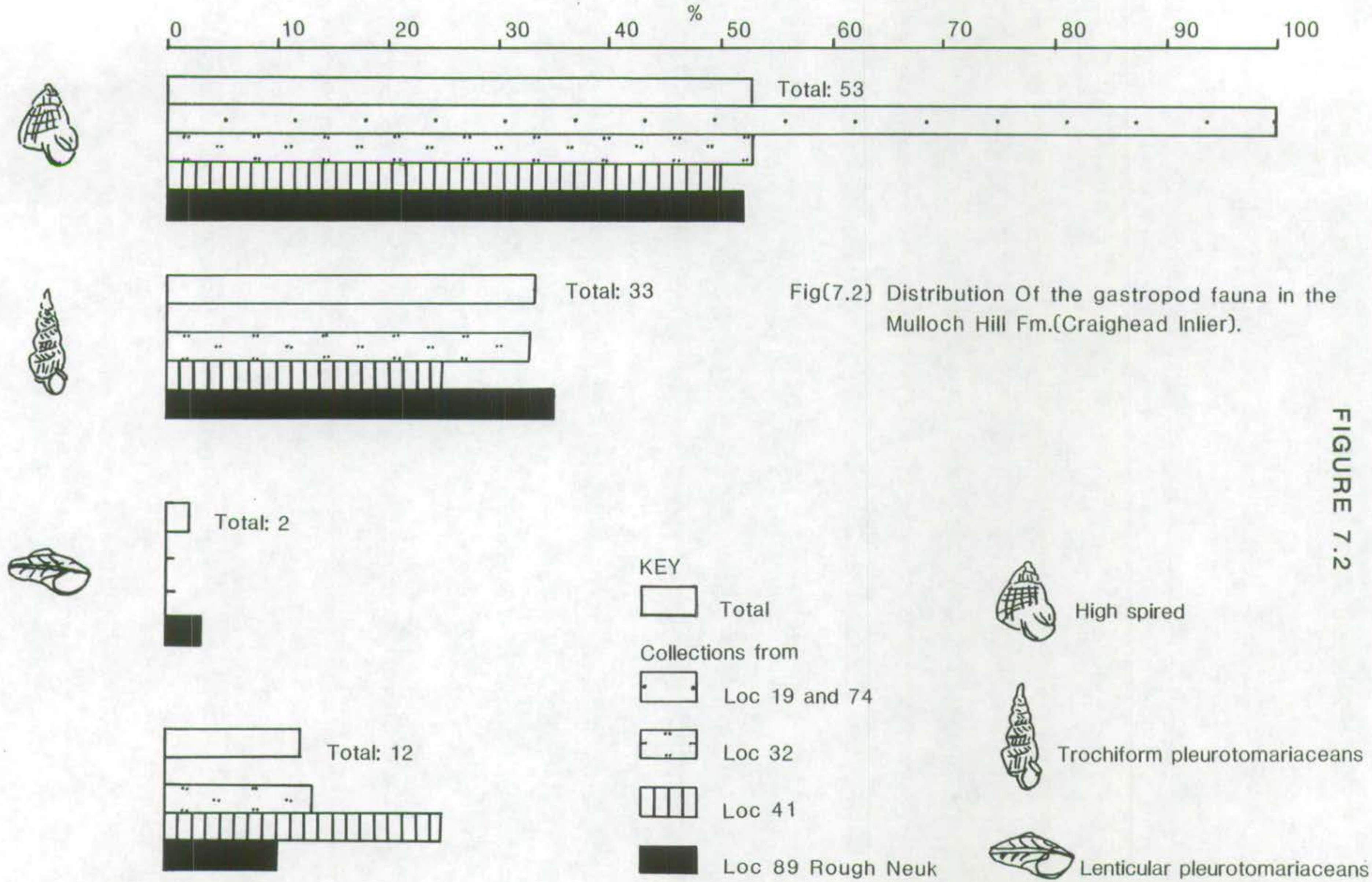
<u>Rough Neuk Starfish Bed</u>

The most significant new palaeontological discovery in the Craighead Inlier was the Rough Neuk Starfish bed. This siltstone bed is less than 10cm thick and occurs above a thickly bedded fine-grained sandstone bed. The upper surface is exposed as a large bedding plane. The low diversity fauna consists dominantly of dendroids and has yielded two completely articulated crinoids, three crinoid calyces, five starfish specimens, ptilodictine cryptostome bryozoan branches, algal fragments and rare small disarticulated brachiopod valves.

Specimens of fragile appearance consisting of a long stem from which club-shaped processes extend, at first sight resemble graptolites (Plate 7.5.7) but . Rickards (pers comm) suggests that these are probably of algal origin; similar forms having been described from Russia. Possibly each club-shaped process was part of a spiral arrangement from a main stem.

All the asteroids are primitive lower Palaeozoic forms. Of the four illustrated in Plate 7.4, two compare with asteroids from the Starfish Beds of the Pentland Hills (Wenlock) (Plate 7.4). These will be the subject of a separate taxonomic and palaeoecological paper (Gale and Ward, in prep).

The crinoids all belong to a single inadunate species (Plate 7.6). Superficially they appear to be calceocrinids, but possess a regular system of heterotomous arm branching rather than the very specialised bilateral heterotomous arm branching



Fig(7.2) Distribution Of the gastropod fauna in the Mulloch Hill Fm.(Craighead Inlier).

FIGURE 7.2

almost all calceocrinids. Under close examination they appear to have only two circlets of plates beneath the primibranchials suggesting affinities with some type of disparid inadunate. No similar crinoids have been documented in literature nor seen by Donovan or Auisch (pers comm). The arm structure, in the crinoids from the Starfish bed superficially resembles that of a cladid such as *Goniocrinus* but the precise pattern of brachiation is different. A more detailed description is in preparation.

The dendroids appear all to be of one species, namely *Dictyonema areyi* (Gurley). The genus is distinguished by the great thickness of the dissepiments and their concave biconvex sides resulting in a rounded oblong mesh shape (Plate 7.5). The thecae are generally invisible. Usually the *Dictyonema* are preserved as flattened black-grey films on the siltstones, up to 2cm in length and frequently the specimens possess stout stems.

A small pedicle valve found on the bedding plane, was identified as *Mendacella mullochensis* (Plate 7.5.6).

Considering that these specimens appear fragile, particularly the starfish and crinoids, the quality of preservation is excellent. Normally, upon death, the muscles and ligaments of crinoids decompose and the crinoids fall to pieces, as do the skeletons of asteroids, disintegrating rapidly into rather small constituents. Complete asteroids in the fossil record are comparatively rare. Thus the preservation of the fauna in the Starfish bed contrasts greatly with the rest of the formation and must reflect rapid burial. Throughout the formation, and the succeeding formations where present, the crinoids are invariably disarticualted, and only disassociated ossicles are found.

Contributing to the diversity of the fauna are trace fossils consisting of single straight burrows up to 0.5cm long, having a circular to oval cross section (Plate 7.9.1-3). In thin section, examined under a petrographic microscope, some of the burrows show concentrations of coarser grained detritus surrounding the wall and are infilled with the host sediment (Plate 7.9.4). Some of the burrows have straight parallel burrow walls whereas in others the walls are not as well defined. Evidence of bioturbation appears only to be present at locality 4, where the texture of the sediment has been disturbed and modified (Plate 7.9.5 & 6).

7.1.3 Glenwells Shale Formation

Owing to poor exposure, it was impossible to determine whether or not the fossils in the Glenwells Shale Formation occurred in specific horizons or were scattered through the sequence.

Solitary corals are similar to *Rhagmophyllum crenulatus* (McCoy), found in the Mulloch Hill Formation (Plate 7.10.1) and there are also some compound corals such as *Halysites* present (Fig. 7.4).

The brachiopod faunas collected from the siltstones near the base are similar to those listed by Cocks and Toghill (1973) for the top of the Mulloch Hill Formation. *Leangella scissa* (Davidson), *Eoplectodonta* sp., *Clorinda* sp., *Dolerorthis* sp., *Skenidioides* sp., *Resserella canalis* (J de C Sowerby) *Leptaena*? *reedi* (Cocks), *Fardenia columbana* (Reed) and *Zygospiraella scotica* (Salter) were recovered from locality 53 (Plate 7.11).

Bivalves are scarce (Plate 7.10.2 and 3) but gastropods are fairly abundant including *Lophospira* sp and *Arjamannia* sp (Plate 7.10.4).

Crinoid branches are relatively well preserved and are significantly different from those seen in the Rough Neuk Starfish Bed, in that the set of arms appear to be pinnulate, suggestive of a camerate crinoid (Plate 7.10.5).

There is a marked decrease in the trilobite fauna, compared with the underlying Mulloch Hill Formation, with only four species identified, namely *Platyiichas scoticus* (Reed), *Encrinurus squarrosus* Howells, *Calymene* s.l. *ubiquitosus* Howells and *Harpidella (Harpidella) newlandensis* (Begg) (Plate 7.12 and Fig. 8.4).

Ostracods have been found for the first time at this level. Even under the SEM the preservation of the disarticulated valves appears poor (Plate 8.10.6). Possibly the ostracods are smooth shelled podocopid ostracods (Siveter, pers comm). The slighty mottled appearance of slabs of the Glenwells siltstone is a result of moderate bioturbation. The preservation of the rest of the elements is relatively good. Brachiopods are almost exclusively disarticulated. All trilobites collected during this study are incomplete and are mainly pygidia and cranidia. There are, however a number of museum specimens with complete exoskeletons, and some of these have been monographed. Crinoids are usually found as loose ossicles, but a number of longer complete branches were found. None of the specimens showed strong evidence of abrasion nor of fragmentation.

In the Glenwells Burn the middle pale-blue shales contain a very different fauna of graptolites (Fig. 8.4). The graptoloides include *Climacograptus cf. rectangularis* (McCoy), *Climacograptus ex. gr. scalaris* (Hisinger) ?*Diplograptus modestus* (Lapworth) indicating an upper *cyphus* zone age, whilst the dendroid fauna consists of *Dictyonema* sp., *Acanthograptus* sp. and *Ptilograptus* sp. (Cocks and Toghill, 1973). Also a single specimen of *Eoplectodonta* sp. and the alga *Cyclocrinites favus* (Nitecki) were found.

Figure 7.4 Fossils present in the Glenwells Shale Formation

Base

Rhagmophyllum crenulatus (McCoy)
Halysites

Ptilodictyne cryptostome ? Stictopora

Dolerorthis sp.
Skeniodoides sp.
Mendacella mullockiensis (Davidson)
Clorinda undata (J de C Sowerby)
Leangella scissa (Davidson)
Eoplectodonta duplicata (J de C Sowerby)
Leptaena reedi (Cocks)
Zygospiraella scotica (Salter)
Eospirigerina gaspeensis (Cooper)
Meifoidia sp.
Lophospira sp.
Arjamannia sp.

camerate crinoid

Platylichas scoticus (Reed)
Encrinurus squarrosus Howells
Calymene ubiquitosa Howells
Harpidella newlandensis Begg

ostracods

Top

Climacograptus rectangularis c.f. (McCoy)
C. ex gr. scalaris (Hisinger)
Diplograptus modestus (Lapworth)
Monograptus revolutus Kurck
M. gregarius Lapworth
Dictyonema sp.
Acanthograptus sp.
Ptilograptus sp.

7.1.4 Newlands Conglomerate Member and Newlands Formation

To date no fossils were found in the Newlands Conglomerate Member, representing the base of the Newlands Formation (Fig. 7.1).

Being the only shelly middle Llandovery in the whole of the Girvan district, or indeed in Scotland, the Newlands Formation is of great palaeontological interest (Fig. 7.5). Cocks and Toghill (1973) have also reported the only known occurrence of a Rhuddanian or Aeronian chonetid, *Strophochonetes* sp. found in the Newlands Formation.

Loose crinoid ossicles are abundant, and only very rarely are the branches preserved. The only graptolites documented from the Newlands Formation are: *Climacogaptus ex. gr. scalaris, Monograptus* sp. and *Dictyonema* sp. (Cocks and Toghill, 1973).

Just as diverse, the trilobite fauna yields over nineteen species. Howells (1982), produced a beautifully illustrated monograph of the trilobites from the Girvan district and other Scottish Silurian trilobites. *Encrinurus*? *newlandensis* (Lamont), *Harpidella* (*Harpidella*) *newlandensis* (Begg) are characteristic of the fauna. Only incomplete exoskeletons were found in the field, particularly of pygidia and free cheeks.

Ostracods are abundant yet very poorly preserved (severely) hindering identification.

7.1.5 Glenshalloch Shale Formation

The fauna occurring in the fissile pale-blue coloured shales in the Glenshalloch Shale is almost exclusively of graptolires (Plate 7.13). Though generally scarce throughout the sequence, the graptoloids are particularly abundant in the laminated shales (locality 129), where their occurrence is restricted to the light olive-grey coloured laminae.

Monograptus gregarius (Lapworth) is dominant, with *Rastrites peregrinus* (Barrande), *Glyptograptus angulatus* (Packham), *Petalograptus palmeus latus* (Barrande), *Monograptus gemmatus* (Barrande), constituting major elements (Fig. 7.6). A few specimens of *Diplograptus thuringiacus* (Munch), *Climacograptus scalaris* (Hisinger), were recovered. Cocks and Toghill (1973) have also reported the occurrence of *Monograptus triangulatus fimbriatus* (Nicholson), *M. cf. communis* (Lapworth), *Rastrites peregrinus/longispinus, Glyptograptus enodis enodis* (Packham), *G. angulatus* (Packham) which date the fauna as lying within the *magnus* subzone of the *gregarius* zone. They also report a slight change in graptoloid composition in that approximately 15m below the base of the Upper Saugh Hill Grits (NS 28270433) they collected *Monograptus* cf. *argenteus* (Nicholson), *M. gregarius* and *Glyptograptus*

Figure 7.5 Fossils present in the Newlands Formation (pers comm. Cocks)

Rugose coral
Favosites
Halysites

Ptilodictyne cryptostomes ? Stictopora

Craniops implicatus (J de C Sowerby)
Dolerorthis (J de C Sowerby)
Skenidioides sp.
Resserella sp.
Clorinda undata (J de C Sowerby)
Stricklandia mullochensis (J de C Sowerby)
Eoplectodonta sp.
Leangella sp.
Meristella sp.
Leptostrophia sp.
Leptaena sp.
Coolina sp.
Strophochonetes sp.
Spirigerina sp.
Meifodia ovalis (Williams)
Pentamerus oblongus (J de C Sowerby)

bivalve fragment
gastropod
crinoids

Climacograptus ex gr. *scalaris*
Monograptus sp.
Dictyonema sp.

Kosovopeltis cunctata (Reed)
Failleana maccalumi (Salter)
Stenopareia glochin Howells
Cyphoproetus externus (Reed)
Decoroproetus farragatus Howells
Harpidella newlandensis (Begg)
Deiphon sp.
Youngia aff. *Y. trispinosa* (Young)
Encrinurus squarrosus Howells
Encrinurus ? newlandensis (Lamont)
Calymene (sili) *ubiquitosa* (Howells)
Acernaspis superciliexcelsis sp. nov.
Dicranopeltis sp.

Hemiarges serus (Reed)
Leonaspis sp.
Anacaenaspis callipareos (Thomson)
Miraspis ultima (Reed)
Globulaspis prominens (Reed)
Odontopleurinae gen. ind.
Ceratocephalina reperta (Reed)

Figure 7.6 Fossils present in the Glenshalloch Shale Formation (Cocks and Toghill 1973)

Middle

Monograptus triangulatus fimbriatus (Nicholson)

M. triangulatus (Harkness) s.l.

M. gregarius

M. cf. *communis* (Lapworth)

M. gemmatus (Barrande)

Rastrites peregrinus (Barrande)

R. longispinus (Perner)

Petalograptus palmeus latus (Barrande)

P. sp.

Glyptograptus enodis enodis (Packham)

G. angulatus (Packham)

Diplograptus thuringiacus (Munch)

Climacograptus scalaris (Hisinger)

Top

Monograptus argenteus (Nicholson)

M. gregarius

Clyptograptus tamariscus tamariscus (Nicholson for Packham)

Figure 7.7 Fossils present in the Pencleuch Shale Formation (Cocks and Toghill 1973)

Monograptus convolutus (Hisinger)

M. leptotheca (Lapworth)

M. clingani (Carruthers) subsp. nov. A

M. cf. *communis*

M. cf. *decipiens* (Törnquist)

Pristiograptus regularis (Törnquist)

Diversograptus ? capillaris (Carruthers)

Rastrites sp.

Petalograptus minor (Elles)

Climacograptus scalaris (Bulman and Rickards)

Pseudoclimacograptus retroversus (Bulman & Rickards)

Orthograptus bellulus (Törnquist)

Monograptus sedgwickii (Portlock)

tamariscus tamariscus (Nicholson) form B Packham. Although this is recognised as a *gregarius* zone, it also possibly represents an *argenteus (leptotheca)* subzone fauna.

7.1.6 Upper Saugh Hill Grit Formation

Largely as a result of poor exposure, neither Cocks and Toghill (1973) nor the author found any fossil remains within the coarse-grained sandstones of the Upper Saugh Hill Grits. Freshney (1959; p30) however, found some unidentifiable brachiopods at his locality 10.

7.1.7 Pencleuch Shale Formation

The Pencleuch Shale is dominated by graptoloids. To date twelve species have been identified including *Monograptus convolutus* (Hisinger), *M. leptotheca* (Lapworth), *M. clingani* (Carruthers), subsp. nov. A, *M. cf. communis*, *M. cf. decipiens* (Tornquist), *Pristiograptus regularis* (Törnquist), *Diversograptus*? *capillaris* (Carruthers), *Rastrites* sp., *Petalograptus minor* (Elles), *Climacograptus scalaris*, *Pseudoclimacograptus retroversus* (Bulman & Rickards), *Orthograptus bellulus* (Tornquist) and *Monograptus sedgwickii* (Portlock) (Cocks & Toghill, 1973) (Fig. 7.7). The major elements are typical of the upper *convolutus* zone, and possibly the fauna is close to the *convolutus* - *sedgwicki* zone boundary as only one single specimen of *Monograptus sedgwickii* (Portlock) has been found by J Floyd (Cocks & Toghill, 1973). Similarly a single specimen of *M.* cf. *sedgwickii* has been found in the Pencleuch Shale of the Main Outcrop.

7.1.8 Lower Camregan Grit Formation

Returning to a more diverse fauna, the fauna of the Lower Camregan Grits consists of rugose corals, stick bryozoa, brachiopods, gastropods and loose crinoid ossicles. The brachiopod fauna is relatively restricted, consisting of twelve species including *Pentamurus oblongus* (J de C Sowerby), *Eocoelia* sp., *Coolinia* sp., *Protochonetes* sp., a smooth atrypid, *Pholidostrophia* (*Mesopholidostrophia*) *salopiensis* (Cocks), *Eoplectodonta* aff. *penkillensis* (Reed), *Dolerorthis* sp., *Stricklandia mullochensis* (Reed), small dalamanellids and rhynchonellids (Fig. 7.8) which indicate an Aeronian age. All of the specimens found were disarticulated.

The trilobites are numerically less diverse than in the underlying Newlands and Mulloch Hill Formations, in that only eight species have been reported by Howells (1982). *Acernaspis* sp. appears to be dominant, and the other species include *Encrinurus confusevarus* Howells, *Stenopareia catathema* Howells, *Astroproetus pseudolatifrons* (Reed), *Warburgella* (*Warburgella*)? sp., *Harpidella* cf. *H. newlandensis* (Begg), *Podowrinella* sp. and *Platylichas* cf. *P. scoticus* (Reed). Only

Figure 7.8 Fossils present in the Lower Camregan Grits Formation (pers comm. Cocks)

Flat Coral
Favosites

Stick bryozoan

Dolerorthis sp.
Small dalmanellid
Pentamerus oblongus
Stricklandia lens
Eoplectodonta aff. penkillensis
Meospholidostrophia solopiensis
Coolinia sp.
Protochonetes sp.
Eocoelia sp.

turbiniform gastropod
Tentaculites
loose crinoid ossicles

Stenopareia catathema Howells
Astroproetus pseudolatifrons (Reed)
Warburgella ?sp.
Harpidella cf. *H. newlandensis* (Begg)
Encrinurus confusevarus Howells
Acernaspis sp.
Podowrinella sp.
Platylichas cf *P. scoticus* (Reed)

incomplete specimens of pygidia and fixed cheeks were found, but complete exoskeletons have been collected.

7.2 THE BIOSTRATIGRAPHY OF THE COASTAL SECTIONS

7.2.1 Craigskelly Conglomerate Formation

No fossils were recovered from the coarse-grained sandstones of the Craigskelly Conglomerate.

7.2.2 Woodland Formations

One of the richest localities in the British Silurian, the Woodland Formation has in excess of thirty species of brachiopod, which are concentrated into specific horizons. At the Haven (locality 213) these levels can be traced for 30cm in the dolomitised limestone, whereas at Woodland Point (locality 231) they occur in the mudstones and can be traced for over 1m and are up to 7cm thick.

Small compound corals such as *Favosites* and *Halysites* are abundant, less so are solitary, rugose corals and dissociated crinoid columnals.

Lapworth (1882, p641) remarked on finding fragments of brachiopods, now identified as *Strophonema grandis* (J de C Sowerby) *Atrypa reticularis* (Linnaeus), and *Eocoelia* sp. and also *Dictyonema* on the western side of Craigskelly (locality 205). The pale-grey colour of these 'hard-bedded gritstones weathering to a yellowish tint and peculiar pink tinge' (Lapworth 1882) misled him into comparing these sediments with the rocks of Saugh Hill. In fact these pale-grey siltstones represent the lower strata of the Woodland Formation.

At Woodland Point the diversity of brachiopods is dramatically higher. *Stricklandia lens* (J de C Sowerby) is dominant and other brachiopods include *Clorinda undata* (J de C Sowerby), *Leptaena* sp. and *Kastrophonema woodlandensis* (Reed) (Fig. 7.9). As well as articulate brachiopods, five inarticulate brachiopod species have been found, including *Lingula* sp., *Craniops implicata* (J de C Sowerby) and *Dinobolus* sp. Although the Woodland Formation contains a higher diversity brachiopod fauna, there are many similarities with the Mulloch Hill Group and Newlands Formation (Fig. 7.10). For example, *Clorinda undata* (J de C Sowerby) occurs also in the Glenwells Shale and Newlands Formation, as do *Meifodia prima* (Williams), *Leangella scissa* (Davidson) and *Eoplectodonta duplicata* (J de C Sowerby). Only a few brachiopods from the Woodland Formation can be correlated with the Mulloch Hill Formation, namely the rhynchonellids, *Zygospiraella scotica* (Salter) and orthids *Resserella canalis* (J de C Sowerby).

Figure 7.9 Fossils present in the Woodland Formation (pers comm. Cocks)

Rugose coral
Halysites
Favosites

Lingula sp.
Philhedrella sp.
Craniops implicata (J de C Sowerby)
Orbiculoidea forbesii (Davidson)
Dinobolus sp.
rhynchonellids
Eospirigerina sp.
Meifodia prima (Williams)
Plectatrypa sp.
? *Glassia compressa*
Zygospiraella scotica (Salter)
Plectatrypa imbricata (J de C Sowerby)
Plectatrypa tripartita (J de C Sowerby)
Clorinda undata (J de C Sowerby)
Stricklandia lens (J de C Sowerby)
Leptostrophia antecedens (Williams)
Saughina pertinax (Reed)
Leptaena haverfordensis (Bancroft)
Giraldiella sp.
Leangella scissa (Davidson)
Kastrophonema woodlandensis (Reed)
Eoplectodonta duplicata (J de C Sowerby)
Triplasia sp.
Brachymmulus sp.
Streptis altosinuata (Holtedahl)
Resserella canalis (J de C Sowerby)

Stenopareia acymata sp. nov.
Hadromeros elongatus (Reed)
Encrinurus squarosus Howells
Calymene ubiquitosa Howells
*Acernaspis superciliexcelsis*sp. nov.
Acernaspis xynon sp.
Lichas silvestris (Reed)
Platylichas scoticus
Hemiarges sp. (Reed)
Leonaspis L. varbolensis (Bruton)
Leonaspis aff. sp.
Leonaspis acarescola Howells
Anacaenaspis callipareos (Thomson)

Figure 7.10 Correlation of the fossils from the Woodland Formation (Glenwells Shale Formation: ○)

	Mulloch Hill and Glenwells Shale Formation	Newlands Formation
Rugose coral	●○	●
Halysites	○	●
Favosites		●
Lingula sp.		
Philhedrella sp.	●	
Craniops implicata (J de C Sowerby)		●
Orbiculoidea forbesii (Davidson)	?	
Dinobolus sp.		
rhynchonellids	●	
Eospirigerina sp.	○	
Meifodia prima (Williams)	○	●
Plectatrypa sp.		
? *Glassia compressia*		
Zygrospiraella scotica (Salter)	●○	
Plectatrypia imbricata (J de C Sowerby)		
Plectatrypa tripartita (J de C Sowerby)		
Clorinda undata (J de C Sowerby)	○	●
Stricklandia lens (J de C Sowerby)	●	●
Leptostrophia antecedens (Williams)		●
Saughina pertinax (Reed)		
Leptaena haverfordensis (Bancroft)	○	●
Giraldiella sp.		
Leangella scissa (Davidson)	○	●
Kastrophonema woodlandensis (Reed)		
Eoplectodonta duplicata (J de C Sowerby)	○	●
Triplasia sp.		
Brachymmulus sp.		
Streptis altosinuata (Holtedahl)		
Resseralla canalis (J de C Sowerby)	?	●
Stenopareia acymata sp. nov.		
Hadromeros elongatus (Reed)		
Encrinurus squarosus Howells	●○	
Calymene ubiquitosa Howells	●○	

Like the brachiopods in the Craighead Inlier, those found at Woodland Point are mostly disarticulated and show minimal evidence of abrasion or fragmentation. An exception has been reported by Ziegler et al (1966), who described a block collected from Woodland Point (US NM locality 10507) of a grey limey mudstone in which there is one horizon of articulated *Stricklandia lens* (J de C Sowerby) orientated in an upright position.

A high diversity trilobite fauna has been recovered from the original site of Mrs Gray's collections (NS 16859520), which may be reached only at low tide. Among the twelve species which have been described by Howells (1982) are: *Stenopareia acymata* Howells, *Encrinurus squarrosa* Howells, *Calymene* (sl) *ubiquitosus* Howells and *Acernaspis superciliexcelsis* Howells. Many of these trilobites can also be found in the Mulloch Hill Group and in the Newlands Formation, at Craighead, but a closer correlation seems to lie with the Mulloch Hill Group (Fig. 7.10).

In marked contrast the overlying banded shales at Woodland Point (locality 235) contain abundant graptoloid specimens of *Monograptus revolutus* and *Rhaphidograptus toernquisti* (Elles and Wood) together with *M. cyphus* (Lapworth), *M. strachani* (Richards & Hutt), *M. gregarius, M. atavus* (Jones), *Climacograptus* aff. *minimus* (Carruthers), *C. normalis* (Lapworth), *C. rectangularius* (Nicholson). *Pseudoclimacograptus hughesi* (Nicholson), *Orthograptus* sp. and ?*Dimorphograptus* sp. which indicate an upper *cyphus* zone age (Cocks & Toghill, 1973) (Fig. 7.11).

In the Haven (locality 216), the banded shales yield *Monograptus revolutus, M. strachani*?, ?*M cyphus*, ?*Diplograptus modestus*, *Climacograptus normalis* and ?*Rhaphidograptus toernquisti* (Plate 7.14). Like the graptoloids in the Glenshalloch Shale (Craighead), they are found in the lighter coloured laminae, but clearly the Woodland Formation graptolites are much older. In fact, some of the Glenwells shale graptolites (Craighead) are of the same species, for example *Monograptus revolutus, M. gregarius, Climacograptus rectangularis* and *Dictyonema* sp. and these are not as diverse or abundant. (Fig. 7.12)

7.2.3 Haven Conglomerate Member and Scart Grit Formation

Apart from clasts of bioclastic siltstones and crinoidal limestones from the underlying Woodland Formation, the Haven Conglomerate Member is unfossiliferous. However, in the succeeding coarse-grained thickly bedded sandstones of the Scart Grits cathodoluminescence studies have detected the presence of thin disarticulated brachiopod valves. The fossils are possibly scattered sparsely through the rock.

Figure 7.11 Graptolites present in the Woodland Formation (Cocks and Toghill 1973)

Woodland Point	**Haven**
Monograptus revolutus (Elles and Wood)	*Monograptus revolutus*
Rhapidograptus toernquisti (Elles and Wood)	*M. strachani*
M. cyphus (Lapworth)	?*M. cyphus*
M. strachani (Rickards and Hutt)	?*Diplograptus modestus*
M. gregarius (Jones)	*Climacograptus normalis*
M. atavus (Jones)	?*Rhapidograptus toernquisti*
Climacograptus sp. nov. aff. *minimus* (Carruthers)	
C. normalis (Lapworth)	
C. rectangularis (Nicholson)	
Pseudoclimacograptus hughesi (Nicholson)	
Orthograptus sp. nov. B	
?*Dimorphograptus sp.*	
Dictyonema sp.	

Figure 7.12 Correlation of the graptolites present in the Woodland Formation.

	Glenwells Shale Formation	Newlands Formation
Monograptus revolutus (Elles and Wood)	●	
Rhapidograptus toernquisti (Elles & Wood)		
M. cyphus (Lapworth)		
M. strachani (Rickards and Hutt)		
M. gregarius (Jones)	●	?
M. atavus (Jones)		
Climacograptus sp. nov. aff. *minimus* (Carruthers)		
C. normalis (Lapworth)		?
C. rectangularis (Nicholson)	●	
Pseudoclimacograptus hughesi (Nicholson)		
Orthograptus sp. nov. B		
?*Dimorphograptus sp.*		
Dictyonema sp.	●	
?*Diplograptus modestus*	●	
?*Rhapidorgraptus toernquisti*		

7.3 TAPHONOMY OF FOSSIL ASSEMBLAGES

Many early German workers (Walther, 1919; Weigelt, 1919, 1927; Richter, 1929) recognised the importance of the processes of death, decay, and disintegration in understanding modes of fossil preservation. But it was not until 1940 that the term 'taphonomy' was introduced to the palaeontological world by Efremov. Generally taphonomy encompasses living organism-substrate relationships, death conditions, pre-burial sedimentology of the remains, and burial and post-burial changes. All of these are very closely influenced by the environmental setting and the ambient sedimentary conditions (Efremov, 1940). Traditionally there are two aspects of the study of taphonomy; 1) biostratinomy, involving the sedimentary history of preservable organic remains, for example abrasion, fragmentation, disarticulation and reorientation and 2) fossil diagenesis, the processes commencing after death; these include replacement, recrystallisation and the decay of tissues.

7.3.1 Preservation of Fossils

Only in exceptional circumstances are soft-bodied organisms preserved in the fossil record (Conway Morris, 1976). Consequently the fossil record is biased towards the hard-shelled elements in the biota. During diagenesis, the composition of the preservable hard parts may be altered. It is thus possible to establish the post-depositional history of a fossil assemblage according to the mode of preservation of the fossil specimens.

In all cases the modes of preservation of fossil specimens examined in this investigation have been examined.

7.3.2 Distribution of Remains

The initial life distribution of organisms may be retained by the arrangement of fossil remains in an undisturbed fossil assemblage. Subsequent transportation or bioturbation may slightly or significantly modify this initial distribution. Brenchley and Newall (1970) showed that the orientation, attitude and spatial distribution of fossils in a fossil assemblage may be a function of the amount of disturbance in that assemblage.

Palaeoenvironmental inferences can be made from the level of articulation of skeletons. Disarticulation is the degradation of skeletons by the bacterial degradation of tissue along natural joints and consequently the otherwise integrated skeleton becomes dissociated into numerous elements. Disarticulation is greatest where the burial rate is slow and shell accumulations are swept along the sea floor and are continually reworked by normal wave disturbance. Also long term surface exposure may result in considerable disarticulation without substantial transportation of the remains. Conversely complete skeletons of sponges, echinoderms, and arthropods are among the best indicators of rapid burial and lack of transport, because of their tendency to undergo rapid post-mortem disarticulation. Moreover clumps of tightly closed bivalved shells are commonly the result of instantaneous burial of in situ organisms.

Middlemiss (1962) pointed out that generally pedunculate, articulate brachiopods are among the most resistant to disarticulation of all bivalved marine invertebrates. He concludes, that a high proportion of disarticulated valves in a sediment, indicates a relatively long period of drifting about on the sea floor before burial. By calculating the pedicle to brachial ratio in disarticulated valves, and measuring the size distribution of brachiopods it can be determined whether or not the fossil assemblage has been transported.

Where the number of pedicle valves to brachial valves varies, the assemblage has been subject to transportation. Transportation away from the area in which the animals lived will result in sorting, due to differences in the competent velocity between opposite valves, when subjected to a succession of currents with varying velocities. Opposite valves having different hydrodynamic characteristics may be deposited separately by waning currents.

Not only is the opposite valve ratio a useful parameter for assessing transportation effects but the orientation of the disarticulated valves also reflects depositional conditions. Boucot (1981) concluded that convex-up shells have been brought to that position of stability during turbulent bottom transport. Shells preserved in the unstable concave-up position, on the other hand must have settled in quiet water. When subjected to turbulence, sufficient to move them any distance along the bottom, they would immediately flip over. Emery's (1968) flume experiments conclusively show that weak bottom currents on the continental shelf are inadequate to overturn concave-up bivalved shells, but the higher velocities encountered in more turbulent shore environments are capable of flipping shells over on to their more stable convex up position.

Orientation studies of disarticulated valves provide information which can be used in evaluating the strength and duration of currents as well as establishing whether or not fossils represent in situ faunas or those transported to their present site.

Craighead Inlier

At Craighead, specifically in the Mulloch Hill Formation, most of the fossils occur in specific horizons, extending for up to 1m in length and up to 8cm thick. At locality 41, nine prominent fossil horizons were examined, which were composed of dominantly disarticulated brachiopods. Between 85-97% of the brachiopods are disarticulated and those brachiopods which are articulated are specifically *Hyattidina* sp. Orientations of the disarticulated valves were measured, showing that up to 62% of the valves were orientated convex-up, a significant percentage (24-26%) however were orientated in inclined positions (Figs 7.13 and 7.14).

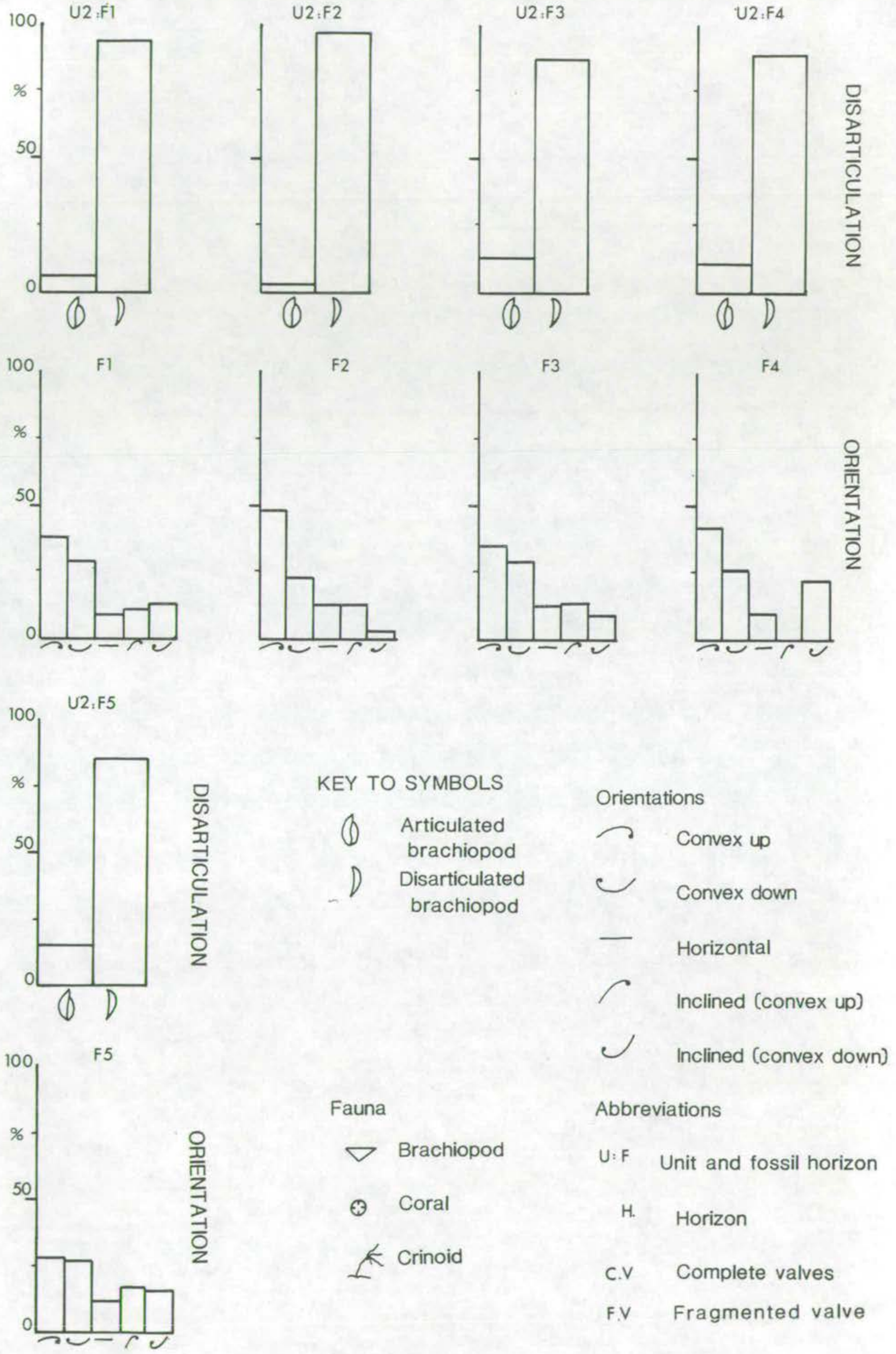
Orientations of disarticulated valves were also measured in the turbidites at Woodland Point (locality 232) (Fig. 7.15 & 16) In both the Mulloch Hill and Woodland Formations, the brachiopods are mainly disarticulated, but in the former there is a slightly higher number of articulated brachiopods (12% compared to 1%) which are namely *Hyattidina*, and there is clear dominance of convex-upward orientated valves (Fig. 7.17). In the Woodland Formation a significant proportion of the valves (9-27%) are resting in an inclined orientation. Of all the valves measured there, 39% were orientated concave-up and 34% were orientated convex-up compared with 17% orientated concave-up and 50% orientated convex up, in the Mulloch Hill Formation.

Furthermore, at the Haven, some of the brachiopod valves in the dolomitised limestone are subtly imbricated. Farrow (1974) described imbricated shells as significant evidence for current regimes interfering with each other.

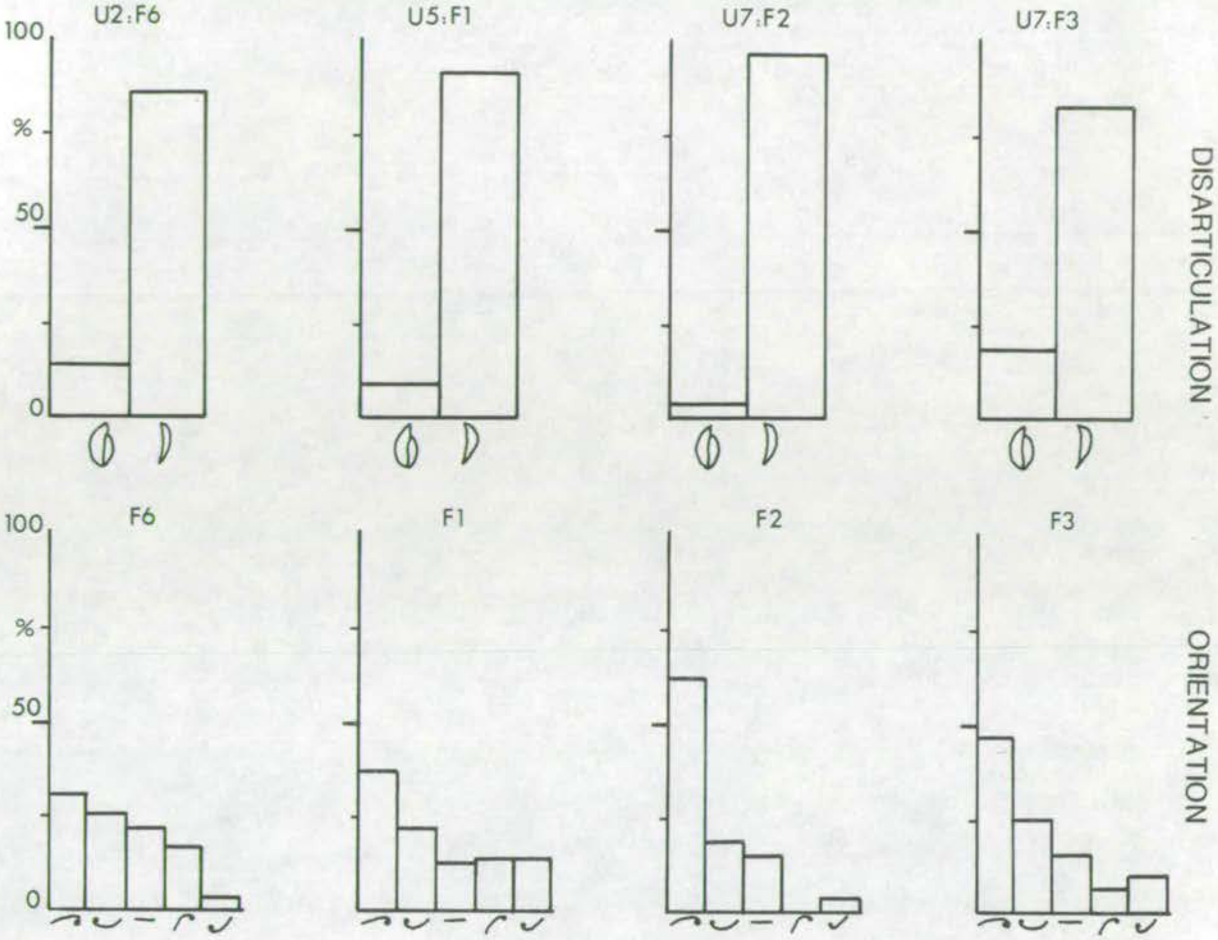
Both the Mulloch Hill and Woodland Formations fossil horizons are laterally persistent, composed of disarticulated valves which may be the product of the transportation of shell debris by storm or turbidity currents. The dominance of convex-up valves in the Mulloch Hill Formation implies current orientation and suggests that the disarticulated brachiopods, after death, and after drifting about on the sea floor were, after some, time rapidly buried by a sudden influx of sand. Partial infilling of the articulated brachiopod shells in the Mulloch Hill Formation and the development of geopetal structures are probably due to drift filling, implying minor current action and prolonged resting of the shells near the sediment-water interface prior to burial.

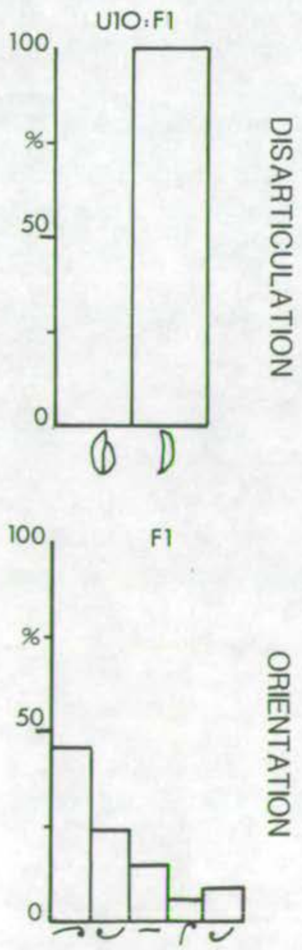
The imbrication of shells in the dolomitised limestone at the Haven indicates persistent wave reworking of dense shell pavements in very shallow water, nearshore environments. Stratigraphically higher, the dominance of concave-up valves indicates generally quiet-water settings where the shells were intermittently stirred up off the sea floor by current, followed by settling.

Uneven pedicle to brachial valve ratios in the brachiopods recovered from the Craighead Inlier (Appendix 3.3), may be the consequence of prolonged exposure of the shells, with or without transport, in moderate to high energy environments (Boucot, 1981); for example, pedicle valves tend to be more abundant in the Mulloch Hill Formation. Not only are the brachiopods concentrated in specific horizons, but the graptolites in the Glenshalloch Shale (Craighead) and Woodland

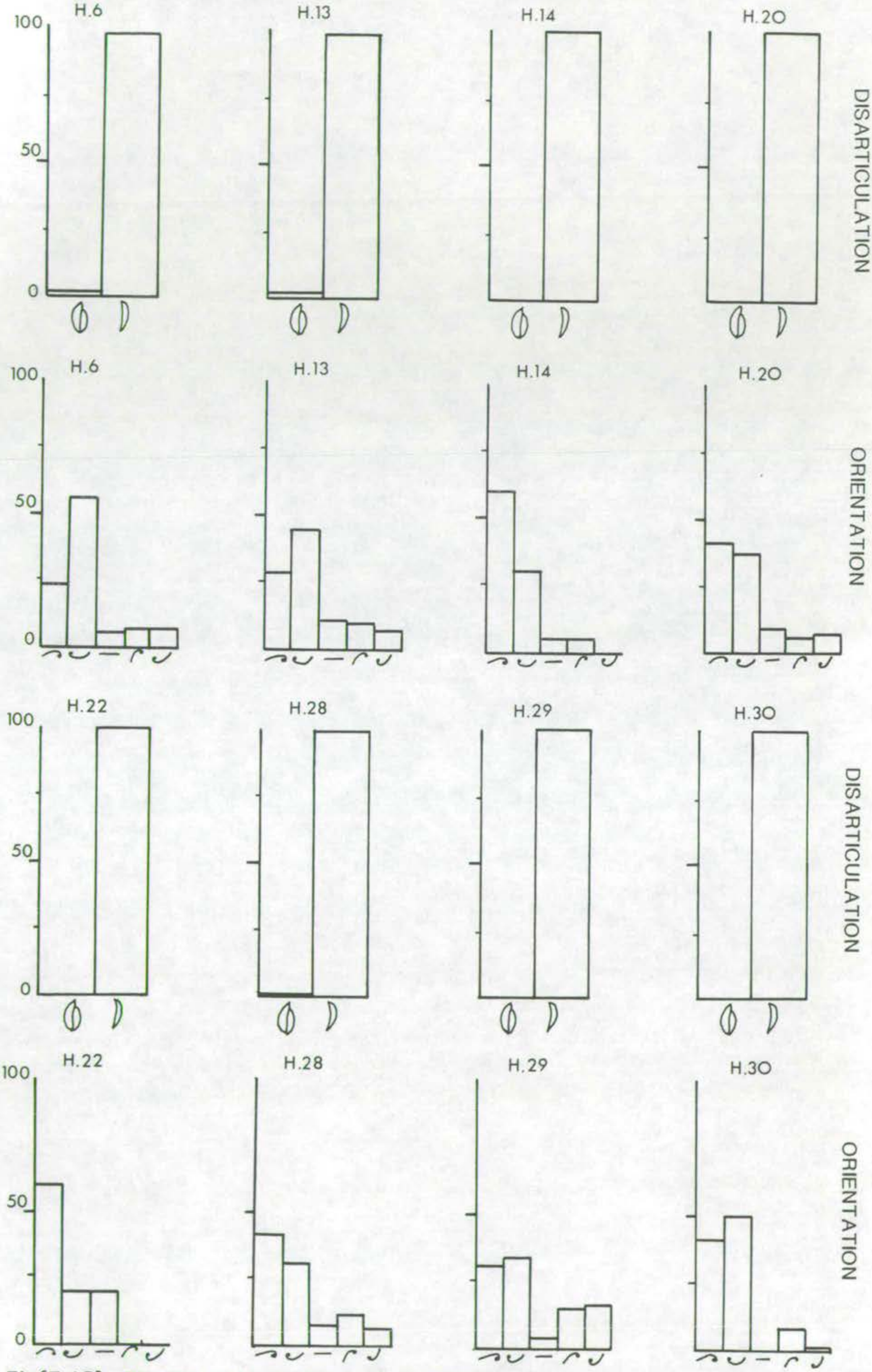


Fig(7.13) Disarticulation ratios and orientations of brachiopods from the Mulloch Hill Formation (locality 41).



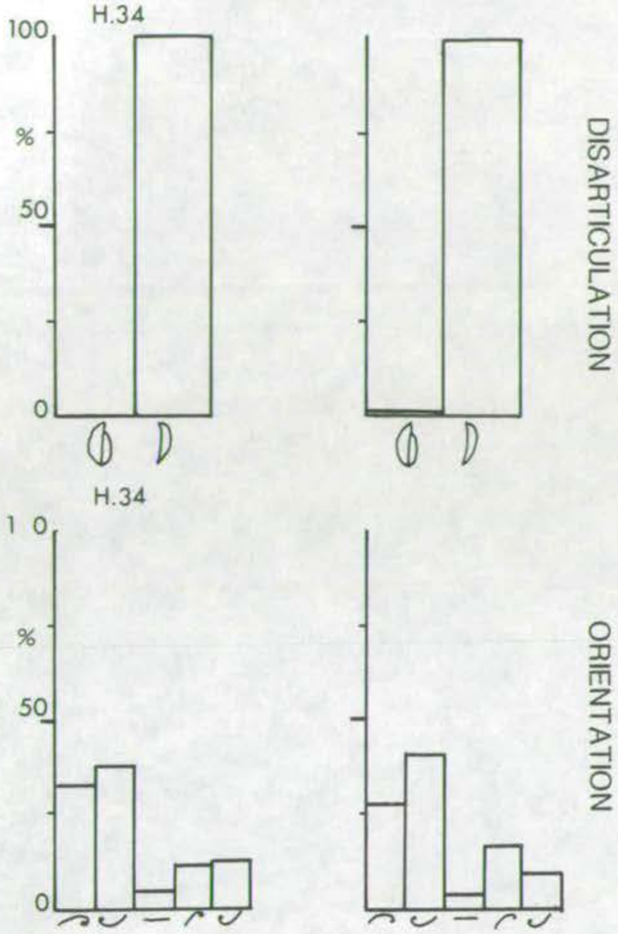


Fig(7.14) Disarticulation ratios and orientations of brachiopods from the Mulloch Hill Formation (locality 41).



Fig(7.15) Disarticulation ratios and orientations of brachiopods from the Woodland Formation (Girvan Shore).

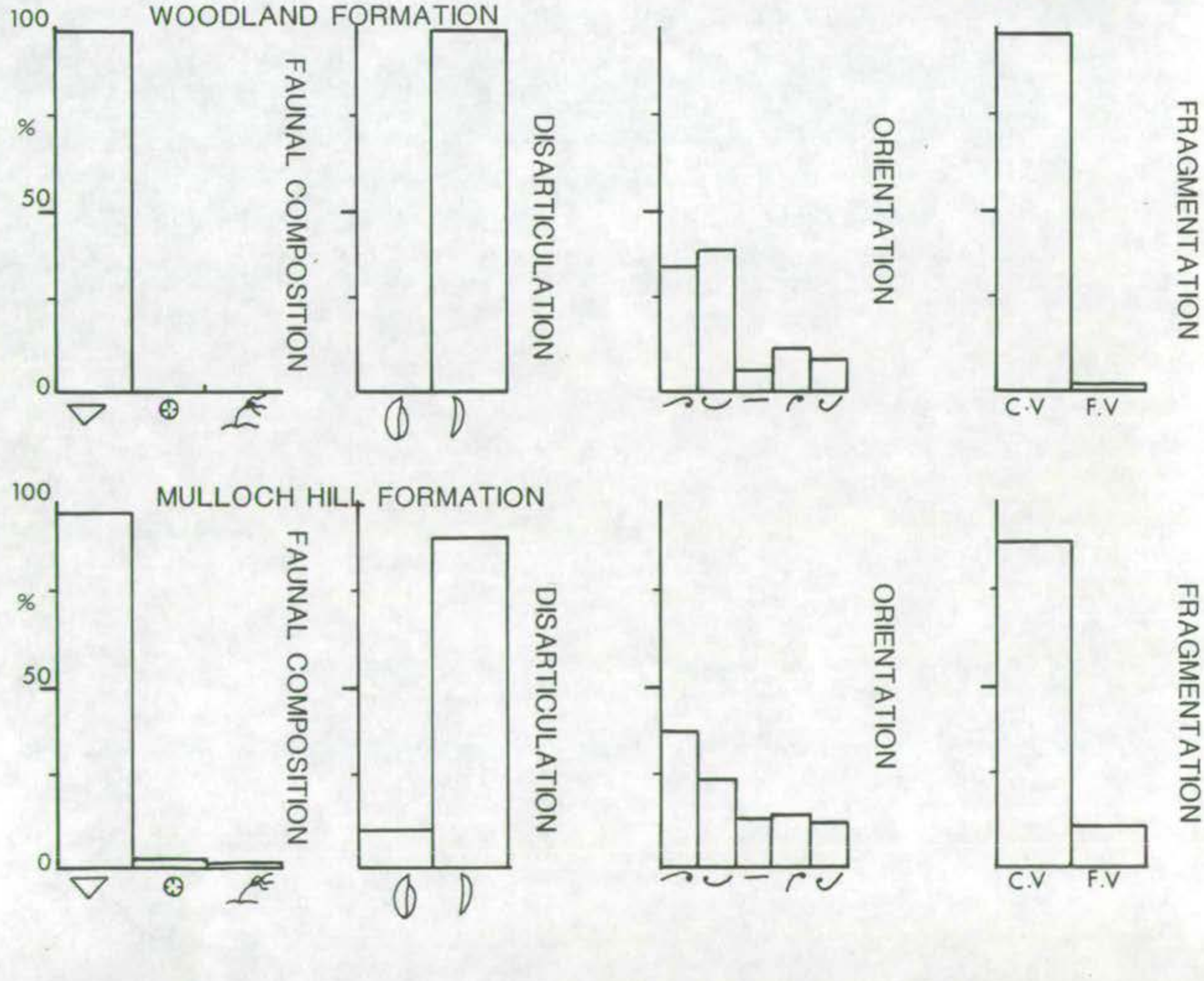
WOODLAND FORMATION



Fig(7.16) Disarticulation ratios and orientations of brachiopods from the Woodland Formation (Girvan Shore).

Fig(7.17) Comparisons of the preservation of brachiopods from the Woodland Formation and the Mulloch Hill Formation.

FIGURE 7.17



Formation (Girvan Shore) are restricted to the light olive-grey coloured laminae of the banded shales where the enclosing sediment was fine enough to preserve them.

7.3.3 Size and Shape Sorting

It has been demonstrated (Lever, 1958; Trewin, 1973; Trewin & Welsh, 1972) that fossils may behave as sedimentary particles under hydraulic conditions, and may also be sorted according to their size and shape.

Size-frequency distributions have been used to distinguish life and death assemblages of fossils (Boucot, 1953), but Craig and Oertel (1966) pointed out that many different size-frequency distributions are the products of the interplay of several factors, which may further be modified by pre- and post- depositional burial disturbance. In the Mulloch Hill Formation the brachiopods display variations in size (Appendix 4) and this suggests that the fossils have not undergone major sorting.

Furthermore, the degree of shape sorting can help to establish whether or not a fossil horizon has been transported. Under certain hydraulic conditions different shaped organisms and components of organisms will behave differently. Thus under-representation of a particular element in a multi component organism would probably indicate that shape sorting had occurred.

According to Brower's (1975) observations on the Silurian crinoids of the Pentland Hills, the occurrence of isolated crinoid columnals only, and the lack of a calyx and arm plates, similar to the situation in the Mulloch Hill Formation, suggests that these columnals have undergone transportation. This is based upon the functional relationship between preservation type and rate of burial where completely preserved crinoids represent the most rapid burial, whereas fully disarticulated specimens indicate complete decomposition prior to entombment and slow burial. Three types of preservation of crinoids were recognised in the Pendland Hills (Brower, 1975)

1. Isolated columnals only, with calyx and arm plates lacking, which may have been transported.
2. Crinoid debris such as loose calyx plates, columnals and arm plates, representing individuals which had partially decomposed and broken up prior to burial.
3. More or less complete crowns, where clearly burial was prior to significant decomposition.

The disarticulated columnals in the Mulloch Hill Formation could have been broken up in transport, but Donovan (pers comm) doubts that these monospecific clusters of columnals could have been generated by transport. More likely the clusters are the product of in situ disarticulation following death but before final burial. The crinoids present in the Rough Neuk Starfish Bed (Craighead) however were buried prior to significant decomposition.

7.3.4 Texture and Structure of Enclosing Sediment

Often the rate of sedimentation is overlooked when considering factors influencing the nature of fossil assemblages. Low sedimentation rates or periods of erosion may cause the preferential removal of sediments and/or fossils to form winnowed shell lags or allochthonous shell beds, which may contain individuals of many generations. On the other hand high rates of sedimentation can produce accumulations of fossil material, dilute and scattered through the rock and yet in situ. Matters are complicated further when sedimentation rates vary.

After burial the fossil assemblage may be disturbed by bioturbation and when intensive it may result in rotation and displacement of fossil remains, so that the appearance of the sediment is altered.

Finally, lithofacies is an important factor in taphonomy from which sedimentation rates and environmental conditions can be, fairly well interpreted or at least partially, understood.

Descriptions of the characteristic lithofacies of each formation have been given in Chapters 2 and 3, accompanied by inferences made upon the environmental conditions at the time of deposition.

7.3.5 Skeletal Damage

A variety of factors cause skeletal damage, viz. abrasion or fragmentation, including amongst others, transportation, predation or degradation. It is difficult to assess which factor was responsible for skeletal damage in particular instances. The damage caused to specimens in hydraulically transported fossil assemblages is related to the abrasive medium as opposed to the distance travelled (cf. Elmore et al. 1979). Breakage is assumed to be evidence for movement, whilst rounding is thought to occur on the relatively massive parts of shells. It has been observed that breakage and rounding are generally associated with an artificially high taxonomic diversity, indicating that more than one community has been amalgamated during movement and transport (Boucot, 1953).

Throughout the Craighead Inlier and the Coastal Sections, evidence for skeletal damage is negligible. This is particularly clear at locality 41 (Craighead) in the Mulloch Hill Formation and at localities 213, 231 (Girvan Shore) in the Woodland Formation where brachiopod shells are thin, yet are only rarely broken or rounded. Moreover bryozoans are particularly sensitive to fragmentation and consequently their intact preservation (in the Craighead Inlier) is strong evidence of rapid burial.

Local transport, however, of these light-weight skeletons at the time of burial may have been possible.

7.4 TRANSPORTED OR IN SITU?

In both the Craighead Inlier and the Girvan Shore, particularly in the cases of the Mulloch Hill and Woodland Formations, the fossils are found in specific horizons. Not only are these relatively thick, (up to 8cm), they are also laterally extensive and subsequently pinch out. Most of the brachiopods are disarticulated, indicating that after death they were not immediately covered by sediment. Although some of the valves are inclined to the sediment there is a slight dominance of convex-up valves in the Mulloch Hill Formation and concave-up valves in the Woodland Formation. The sole exception is the block described by Ziegler et al. (1966) with conjoined (*Stricklandia*) valves in apparent life position. Taking into consideration the sedimentological evidence and looking at each Formation individually:

7.4.1 Mulloch Hill Formation

In the Mulloch Hill Formation, the fossil horizons are found near the base or top of individual units; the disarticulated valves show a slight dominance of convex-up orientations and occasionally are infilled with mud. Bioturbation is moderately developed in some units indicating a stable substrate. After death and prior to burial, the brachiopods drifted along the sea floor, and eventually the muscles decayed resulting in disarticulation. Relatively long periods of drifting may account for the unequal pedicle to brachial valve ratio. Some of the valves were flipped over onto their most stable orientation, namely convex up. Then, however, the valves were rapidly buried, as indicated by some of their inclined positions and the presence of sporadic small pebble to granule grade clasts, which include a granite clast (2cm diameter) found at locality 41.

7.4.2 Woodland Formation

In the Woodland Formation the fossils are concentrated in the mud layers between the turbidites at Woodland Point (locality 232). By contrast with the Mulloch Hill Formation, the ratio of concave-up and convex-up valves is about 1/1, and as some of the valves are inclined to the bedding plane, it appears that the fossils have been transported by turbidite currents, accounting for their more random orientation. The single block of articulated, upright *Stricklandia lens* (J de C Sowerby) described by Ziegler et al. (1966), which clearly appear to be in their original growth position, must indicate very rapid deposition - an obrution deposit which by chance preserved a living colony. No other such life associations were found in the course of the present study, although over 1,000 other brachiopod valves (99% disarticulated) have been found.

There does not seem to be evidence of size sorting, nor do the thin shells in either Craighead or the Girvan Shore appear fragmented, therefore the fossils have not travelled far from their original habitat, perhaps only a few metres or so.

7.4.3 Rough Neuk Starfish Bed

Undoubtedly the intact crinoids and starfish present in the Rough Neuk Starfish Bed (Craighead) were buried prior to significant decomposition; they otherwise would have fallen to pieces rapidly. Three examples of British 'starfish beds' have been described by Goldring and Stephenson (1972): 1) Middle Lias (L. Jurassic) of Dorset, 2) Upper Silurian Leintwardine 'starfish bed' and finally 3) Upper Ordovician starfish bed of Girvan, Scotland. In the first example, death is accounted for by smothering, in the second the organisms were buried by fine-grained turbidites with no subsequent reworking and in the Girvan, Upper Ordovician Starfish bed, Goldring and Stephenson attribute the excellent preservation of the fauna and diversity to rapid burial in a turbulent shallow water environment, associated with lateral displacement of the material.

Recently, Harper (1982) described this Upper Ordovician Starfish bed, which occurs in Lady Burn, Craighead. Besides starfish, the bed contains a very rich and diverse fauna, numerically dominated by brachiopods and trilobites. Their preservation is excellent, and most specimens are complete and articulated and rarely show the affects of abrasion or breakage as would be expected to result from high energy conditions or transport. Harper (1982) points out that most of the benthonic faunas have been transported downslope and advocates that burial occurred during sudden downslope movement of both sediment and faunas, accounting for the presence of a mixed fauna of shelf and slope derivation.

Several horizons rich in starfish occur in the Pentland Hills (Peach and Horne, 1899 and pers comm, Bull).

Cain (1968) established that in the modern comatulid *Antedon bifida*, the pinnules begin to disarticulate within half an hour of death, so preservation of such structures indicates rapid burial in addition to minimal transportation. Obrution deposits preserve living organisms by rapid burial and smothering of the fauna or flora, and this catastrophic event may account for the excellent preservation of the Rough Neuk Starfish Bed. The fauna may have been engulfed by a cloud of mud, smothering the starfish and crinoids resulting in the blocking up of their ambulacral system by fine sediment, comparable with other examples discussed by Seilacher et al. (1985)

7.5 COMMUNITY VERSUS ASSOCIATION

One of the major goals of marine palaeoecology is the description of community structures and their evolution, with the ultimate aim of developing general models and relating them to environmental parameters. Cocks and Toghill (1973) discussed the significance of the shelly faunas occurring in the Girvan district and correlated the faunas with the depth-influenced communities defined in the Llandovery of the Welsh Borderlands (Ziegler et al., 1968). Ziegler et al. (1968) provided pictorial representations and descriptions of the Silurian marine communities of the Welsh Borderlands, defining five communities namely the *Lingula, Eocelia, Pentamerus, Stricklandia* and *Clorinda* communities.

In the Craighead Inlier Cocks and Toghill (1973) described a change in the brachiopod fauna passing from a low-diversity *Cryptothyrella* (referred to here as *Hyattidina*) community in the Mulloch Hill Conglomerate (Fig. 7.15) (ecologically correlating with Welsh Borderlands *Eocoelia* community), a high diversity *Cryptothyrella* community in the Mulloch Hill Formation, then a *Clorinda* community, followed by the graptolite-bearing Glenwells Shale. The Newlands Formation was thought to contain both *Stricklandia* and *Clorinda* communities, which Cocks and Toghill interpret as colonisation by brachiopods near to the edge of the local shelf. Along the Girvan Shore they recognise an upward change from a *Stricklandia*, through a *Clorinda* community in the Woodland Formation, to the graptolite-bearing sequence, indicating a transgressive sequence.

In this investigation there is substantial evidence that many of the fossils may have been locally transported or drifted along the sea floor and the question thus arises as to how valid Cocks and Toghill's (1973) communities are? In order to answer this question, one must define accurately the meaning of a palaeocommunity.

The originator of the term 'community' was Petersen (1911, 1913, 1915, 1918) who defined it as a recurrent combination of organisms found living together. Thereafter the terms 'association' and 'community' became ambiguous since both are based on recurrent patterns in constituent taxa and different workers disagreed over which environmental variables have predominant influence (cf Bergström, 1968; Bretskey et al., 1969; Anderson, 1971; Tipper, 1975; McKerrow, 1978; Raup and Stanley, 1978).

Perhaps the most clear cut definitions are those proposed by Lockley (1983) who adopted and somewhat extended Pickerill and Brenchley's (1975, 1979) conceptions. Lockley recognised that recurrent assemblages of similar composition represent in situ residua of biological communities. Any evidence of reworking or physical environmental control, however, disqualifies the assemblage from interpretation as an authentic community.

Lockley's definitions are as follows:

1) An 'assemblage' refers to a single sample collected from a particular horizon. This assemblage may be transported, partially disturbed (Scott, 1974) or an in situ residue.
2) An 'association' denotes a group of assemblages all displaying similar recurrent patterns of species composition. From one association to the next its origin may vary.
3) A 'palaeocommunity' represents an association or group of associations which is thought to represent one distinctive biological entity. Only associations which are closely related in terms of taxonomic composition, paleogeography, age and facies preferences may be designated community.

Names for most of the Silurian associations are derived from the commonest brachiopod species, reflecting the commonly held view that these animals were dominant in the environment in question (summaries see Boucot, 1975; Cocks and McKerrow, 1978, 1984). Upon closer inspection of the skeletal components of some of the Silurian sediments, the dominance of brachiopods can only be seen as an artefact of preservation, since some organisms (especially echinoderms and bryozoans) that disarticulated more easily after death may have actually been more abundant in their environment than they now appear to be (for example Jaanusson, in Jaanusson et al. 1979; Amsden, 1981). Nonetheless, Silurian brachiopods are abundant and often well preserved in a wide range of sediment types and therefore it is widely accepted that in such circumstances, the associations are named after the brachiopod taxa.

As with so many concepts, there are a number of inherent problems.

1) Many workers presume that the fossils are in situ residua of a biological community and may thus neglect the effects of reworking or selective transport. These factors may alter the composition of a community and may introduce faunal elements, which originally occupied slightly different habitats.
2) The effects of condensation, i.e. the phenomenon of shell accumulation on the sea floor due to non-deposition (Heim, 1934) have also tended to be overlooked. Due to environmental, biotic, or diagenetic factors, especially in shallow shelf deposits, this phenomenon may also lead to the mixing of the fauna (Fürsisch, 1978).
3) Fossils occurring together in an association may not in fact have been strictly contemporaneous. The accumulated shells of successive faunas over many

years may occupy only a thin fossil band but give a spurious impression of a greater variety of organisms than actually lived together.

4) Differential mortality rates among species may affect the balance of specimens present. A species which had a longer life span than another species would be represented in the collections by fewer specimens relative to the whole community (Ziegler et al, 1968).

5) The fossil record is taphonomically biased, so that usually the hard parts of the skeleton alone are fossilised whereas soft bodied elements are generally not preserved. The nature and preponderance of soft bodied elements cannot be adequately known and therefore their presence and significance in the community is very hard to estimate.

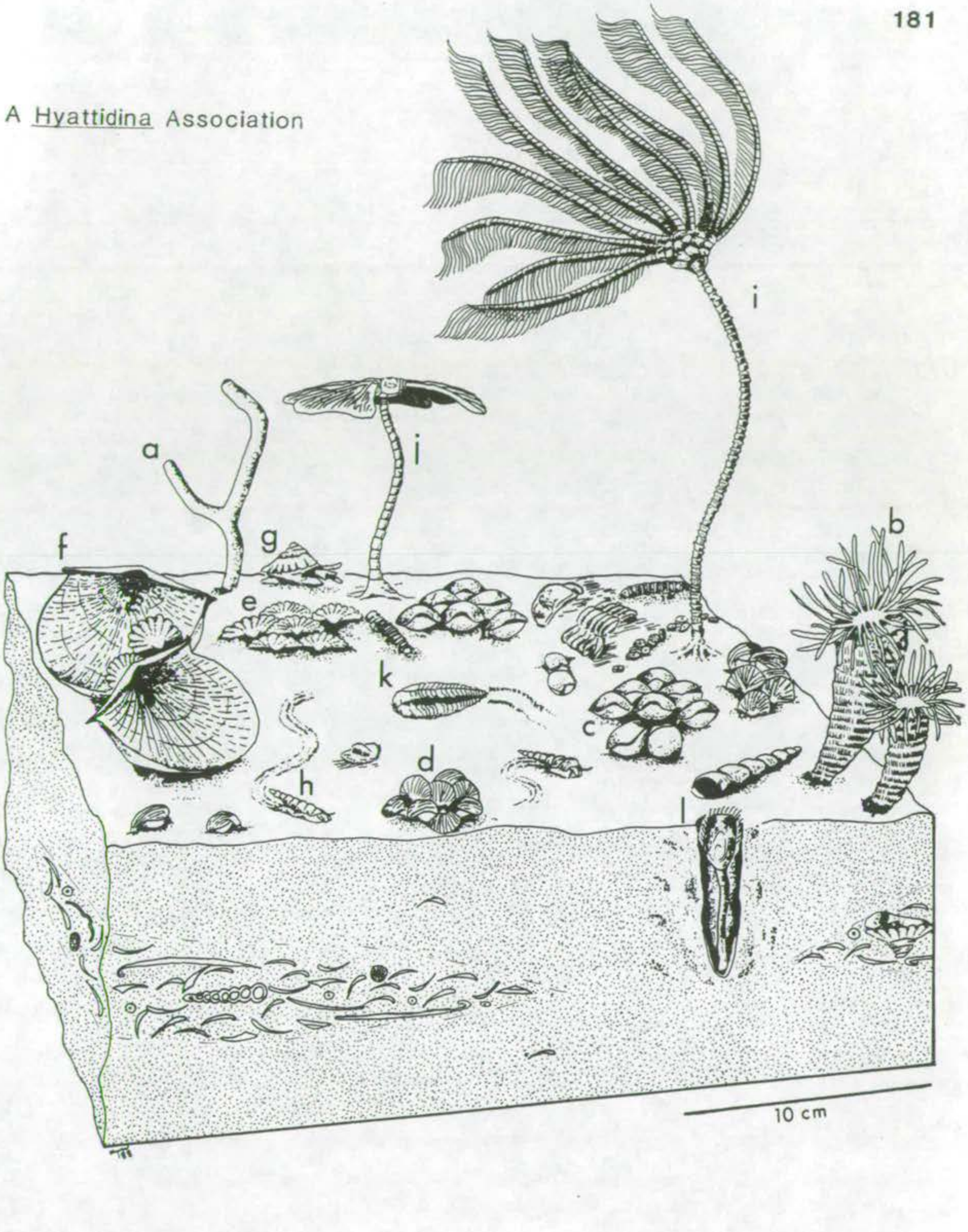
6) In a biological sense the term community should imply interactions and interdependence among component species. Since extrapolation from present day to Palaeozoic times is rather hazardous it is extremely difficult to measure the degree of interaction.

Since communities are not strictly homologous they actually represent accumulations of fossil remains over a period of time, rather than a census taken at one instant (Anderson, 1971). In order to accommodate for this, the term 'time averaged fossil community' has been introduced.

Some authors (e.g. Williams, 1976; Hurst, 1979; Lockley, 1980) have tended to avoid the term community because of the ambiguities arising from the fine distinction between 'association' and 'community', and the inherent biological implications. Williams (1976) used the mathematical label 'set' for faunal groupings defined by cluster analysis.

Here, however, while accepting these problems Lockley's 1983) scheme is generally used and it is preferred to call the faunal groupings 'associations' as opposed to 'communities'. The practice of naming the associations after a genus, which in the sense of Johnson (1972) and Lockley (1983), is dominant or characteristic is one of the most abundant and is here continued. In this sense the Craighead Inlier shows a gradual sequence of a low diversity *Hyattidina*(?) Association, a high diversity *Hyattidina*(?) Association (Fig. 7.18), a *Clorinda* Association is equivalent to *Stricklandia-Clorinda* Association. Likewise the Woodland Formation Association complies with the *Stricklandia-Clorinda* Community, as defined by Cocks and Toghill (1973).

A Hyattidina Association



a Ptilodictya sp.

b streptelasmatid coral

c Hyattidina ? angustifrons

d dalmanellid

e Zygospiraella scotica

f Eostropheodonta mullochensis

g Liospira sp.

h Loxonema sp.

i crinoid

j Petalocrinus

k Calymene ubiquitosus

l burrow

Fig(7.18) Diagrammatic illustration of a Hyattidina Association (modified form McKerrow,1978).

Plates 7.1 - 7.14 (Chapter 7)

Plate 7.1

Calcareous alga, Rugose Coral, Sponge

MULLOCH HILL FORMATION

Figures 1-2 *Cyclocrinities favus* (Nitecki)

1. Lateral view of internal mould, TW.89.01 x 4

2. Lateral view of external mould, TW.89.02 x 5

Figure 3 *Rhagmophyllum crenulatus* (McCoy)

3. Lateral view of internal mould of a corallite, TW.89.03 x 6

Figures 4-5 Sponge

4. Sponges encrusting a brachiopod, TW.89.04 x 4

5. Sponges, TW.89.05 x 5

Figure 6 *Heliolites* sp.

6. Lateral view, TW.32.06 x 7

PLATE 7.1

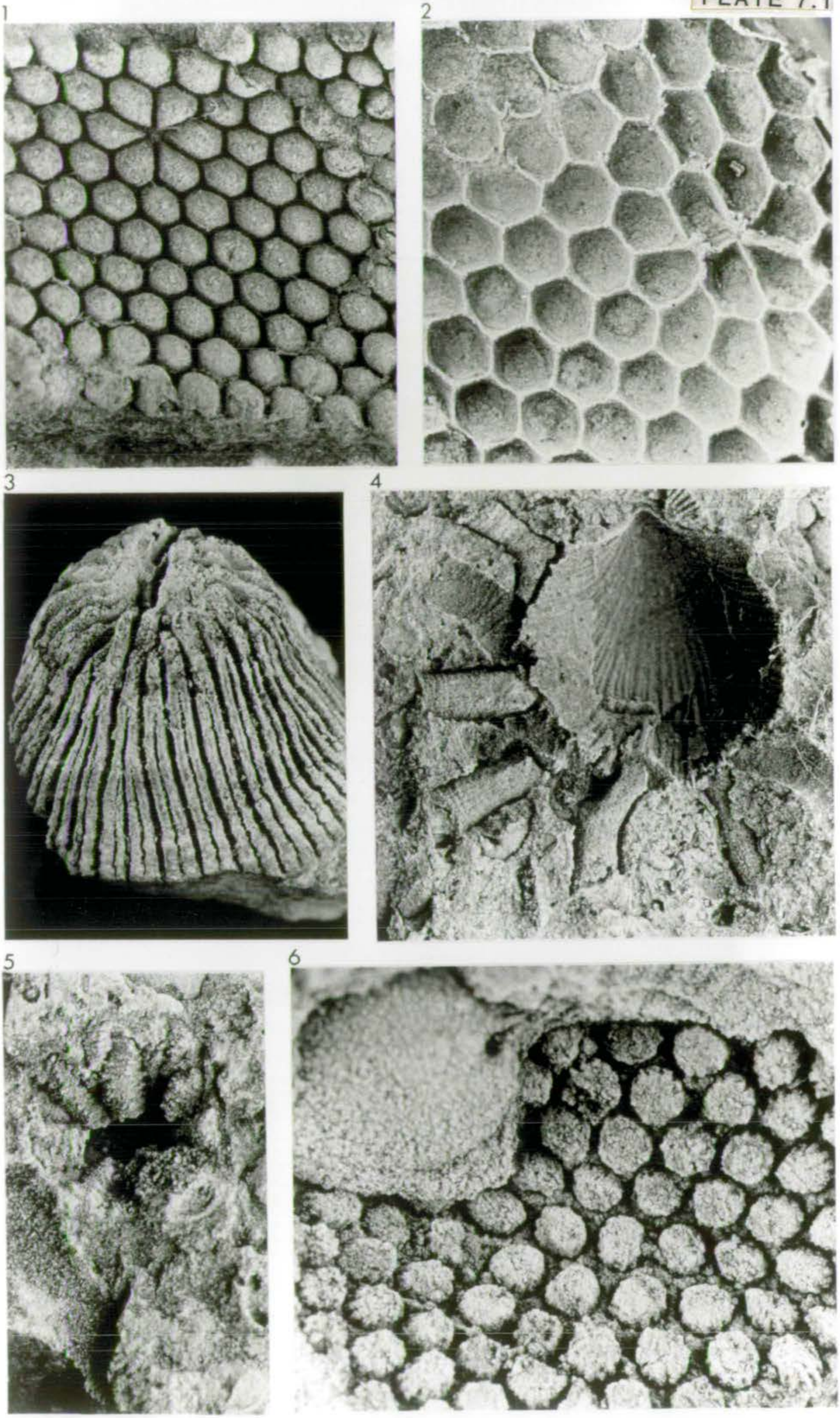


Plate 7.2

Bryozoa, Mollusca

MULLOCH HILL FORMATION

Figure 1 Ptilodictyine cryptostome ?Stictopora

1. Lateral view of external mould, colony, TW.89.08 x 3

Figure 2 Sponge or bryozoan

2. Lateral view of external mould, colony, TW.89.09 x 3

Figure 3 *?Grammysia* cf. *undata* (Sowerby)

3. External mould of right valve, TW.89.10 x 2

Figure 4 Nautiloid Cephalopod

4. Lateral view of incomplete internal mould, orthocone, TW.89.11 x 3

Figure 5 *Orthoceras* sp.

5. Lateral view of incomplete internal mould, orthocone, TW.89.12 x 3

Figure 6 *Hyolithes* sp.

6. Lateral view of incomplete internal mould, orthocone, TW.89.13 x 3

PLATE 7.2

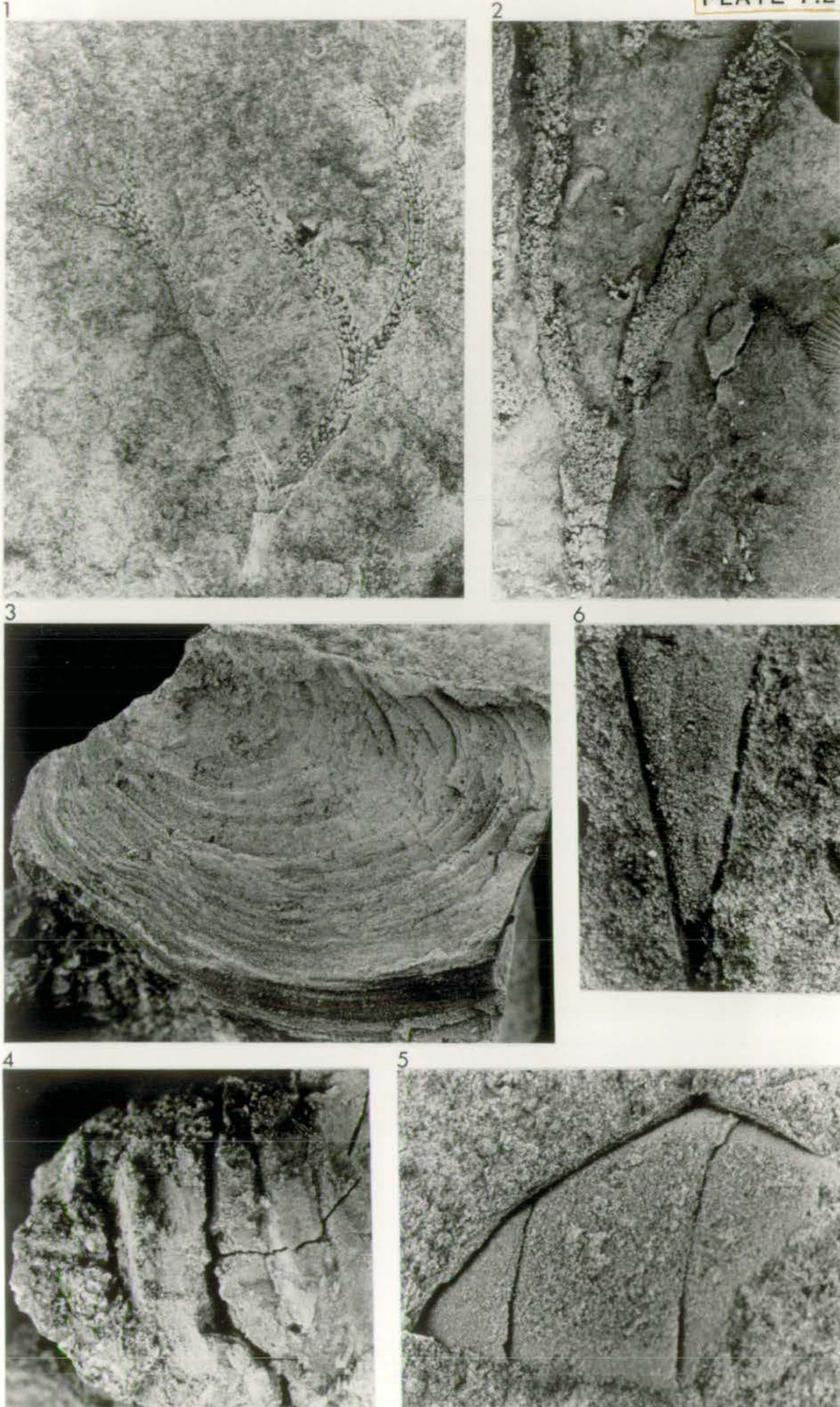


Plate 7.3

Gastropods

MULLOCH HILL FORMATION

Figure 1 Murchisoniacean indet.

1. Lateral view of latex replica of external mould, helicocone, TW.41.14 x 3

Figures 2-5 *Lophospira* sp.

2. Lateral view of latex replica of external mould, helicocone, TW.89.15 x 2

3. Lateral view of latex replica of external mould, helicocone, TW.89.16 x 2

4. Lateral view of latex replica of incomplete external mould, helicocone, TW.19.17 x 2

5. Lateral view of latex replica of incomplete external mould, helicocone, TW.32.18 x 3

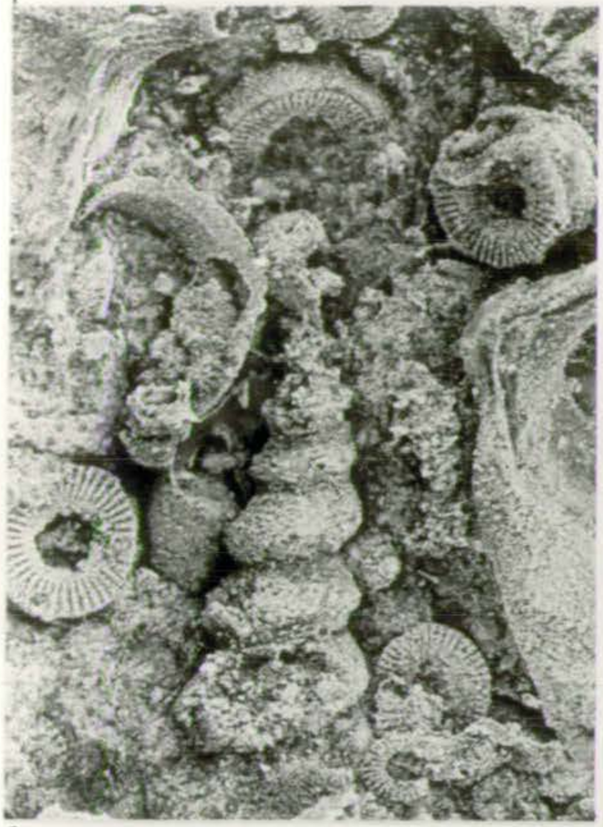
Figure 5 & 6 (right) *Loxonema* sp.

5. Lateral view of latex replica of incomplete external mould, helicocone, TW.32.19 x 3

6. Lateral view of latex replica of incomplete external mould, helicocone, TW.32.20 x 3

PLATE 7.3

1



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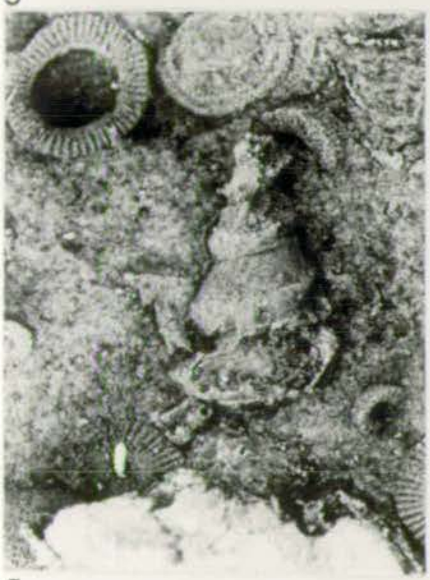
3



4

5

6

Plate 7.4

Asteroids

ROUGH NEUK STARFISH BEDS

Figures 1-5 Asteroids

1. Species A. Probably Taeniactinidae. Oral surface of individual in which ossicles have been slightly disrupted. Note well developed admarginals, with large, elongated axillary (arrowed in Fig. 1c). Undescribed, but compares best with *Taeniactis* from Starfish Bed of Pentland Hills (Wenlock). TW.89.21. Scale: 1a X, 1b X, 1c X.

2. Species B. Scuchertiidae, undescribed genus. Oral surface of individual in which ossicles have been disrupted and partly displaced. Adambulacrals are well developed, but admarginals are small or absent. Disc on aboral side would have been inflated in life, with flexible integument including numerous small granular ossicles (arrowed in 2c). Note large, prominent mouth-angle plates, arrowed in 2b.
TW.89.22. Scale: 2a X, 2b X.

3. Species C. *Schuchertia* sp. nov. Oral aspect of well-preserved individual. Compares best with *C. wenlocki* Spencer (from Pentland Hills Starfish Bed), but differs in smaller, unridged madreporite, and details of oral ossicles. Axillary admarginal arrowed.
TW.89.23. Scale: 3a X, 3b X.

4. Species D. Small asteroid, ossicles partially dissociated, in oral aspect. Possibly *Urasterella*, from the sigmoidal shape of the adambulacrals, but insufficiently well preserved to be determined accurately.
TW.89.24. Scale: X.

5. Indeterminate fragment of asteroid.
TW.89.25. Scale: X.

PLATE 7.4

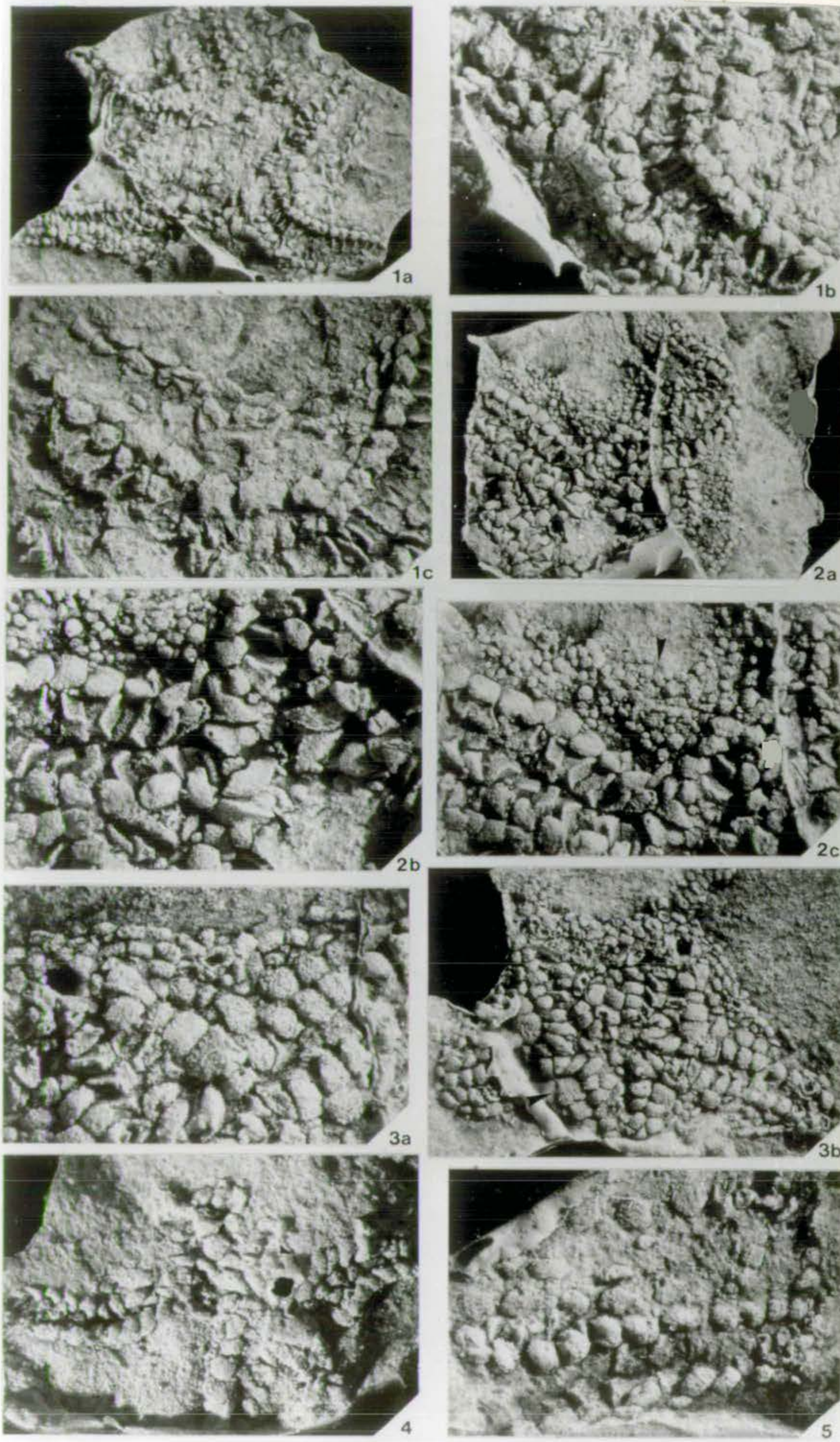


Plate 7.5

Dendroids

ROUGH NEUK STARFISH BED

Figures 1-6 *Dictyonema* sp.

1. Lateral view of incomplete rhabdosome, carbonised periderm, TW.89.26 x 2
2. Lateral view of incomplete rhabdosome, carbonised periderm, TW.89.27 x 3
3. Lateral view of incomplete rhabdosome, carbonised periderm, TW.89.28 x 3
4. Lateral view of incomplete rhabdosome, carbonised periderm, TW.89.29 x 3
5. Lateral view of incomplete rhabdosome, carbonised periderm, TW.89.30 x 3
6. Lateral view of incomplete rhabdosome, carbonised periderm, small *Mendacella* sp. pedicle valve, TW.89.31 x 3

Figure 7 Alga

7. Lateral view of incomplete branch, TW.89.32 x 2.5

PLATE 7.5

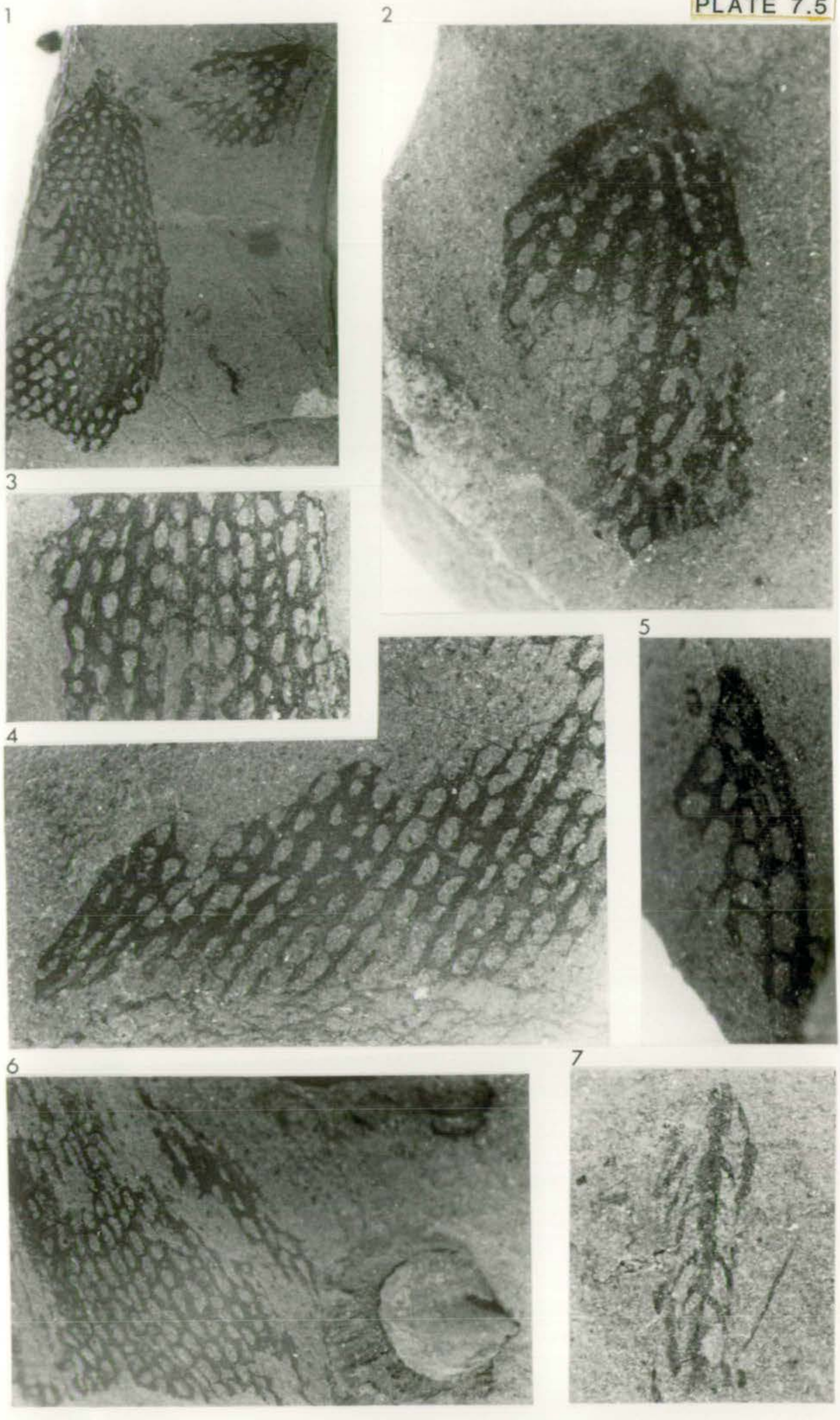


Plate 7.6

Crinozoans

ROUGH NEUK STARFISH BED

Figure 1-3 Inadunate crinoid

1.	Internal mould of complete crinoid,	TW.89.33 x 10
2.	External mould of complete crinoid,	TW.89.32 x 13
3.	Latex replica of exterior of complete crinoid,	TW.89.33 x 6

Figures 4-5 Inadunate crinoid

4.	Internal mould of calyx, arms and stems,	TW.89.35 x 13
5.	Latex replica of calyx and arms,	TW.89.35 x 12

Figures 6-7 Inadunate crinoid

6.	External mould of calyx and arms,	TW.89.36 x 13
7.	Internal mould of calyx and arms,	TW.89.37 x 10

PLATE 7.6

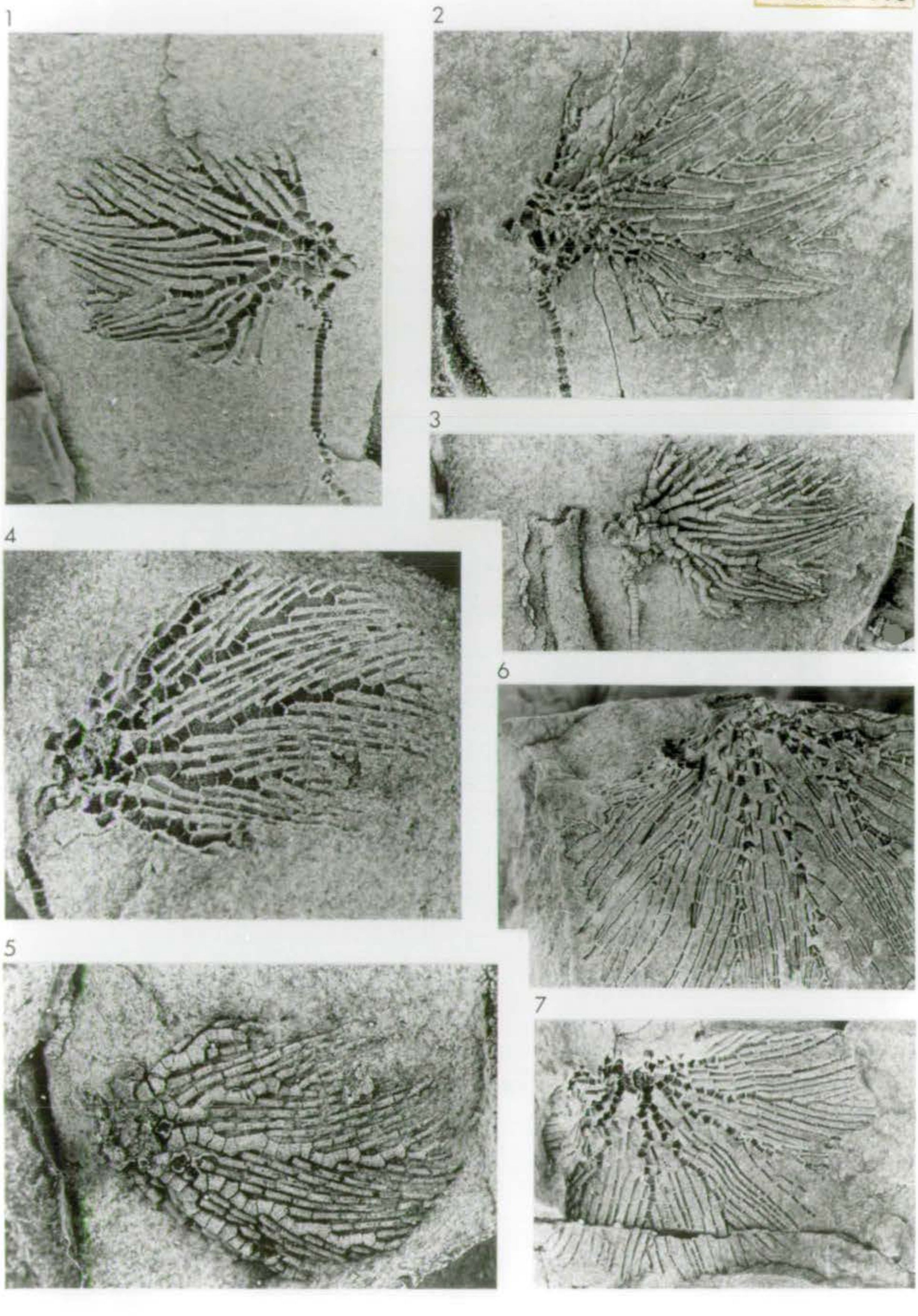


Plate 7.7

Crinozoans

MULLOCH HILL FORMATION

Figure 1 *Petalocrinus* sp.

1. External, incomplete brachia plate, TW.89.38 x 2.5

Figures 2-6 Pelmatozoan

2. External, incomplete stem TW.32.39 x 3
3. External, incomplete stem, TW.89.40 x 4
4. Latex replica of ossicle, TW.89.41 x 3
5. Latex replica of ossicle, TW.89.42 x 3
6. Latex replica of ossicle, TW.89.43 x 3

PLATE 7.7

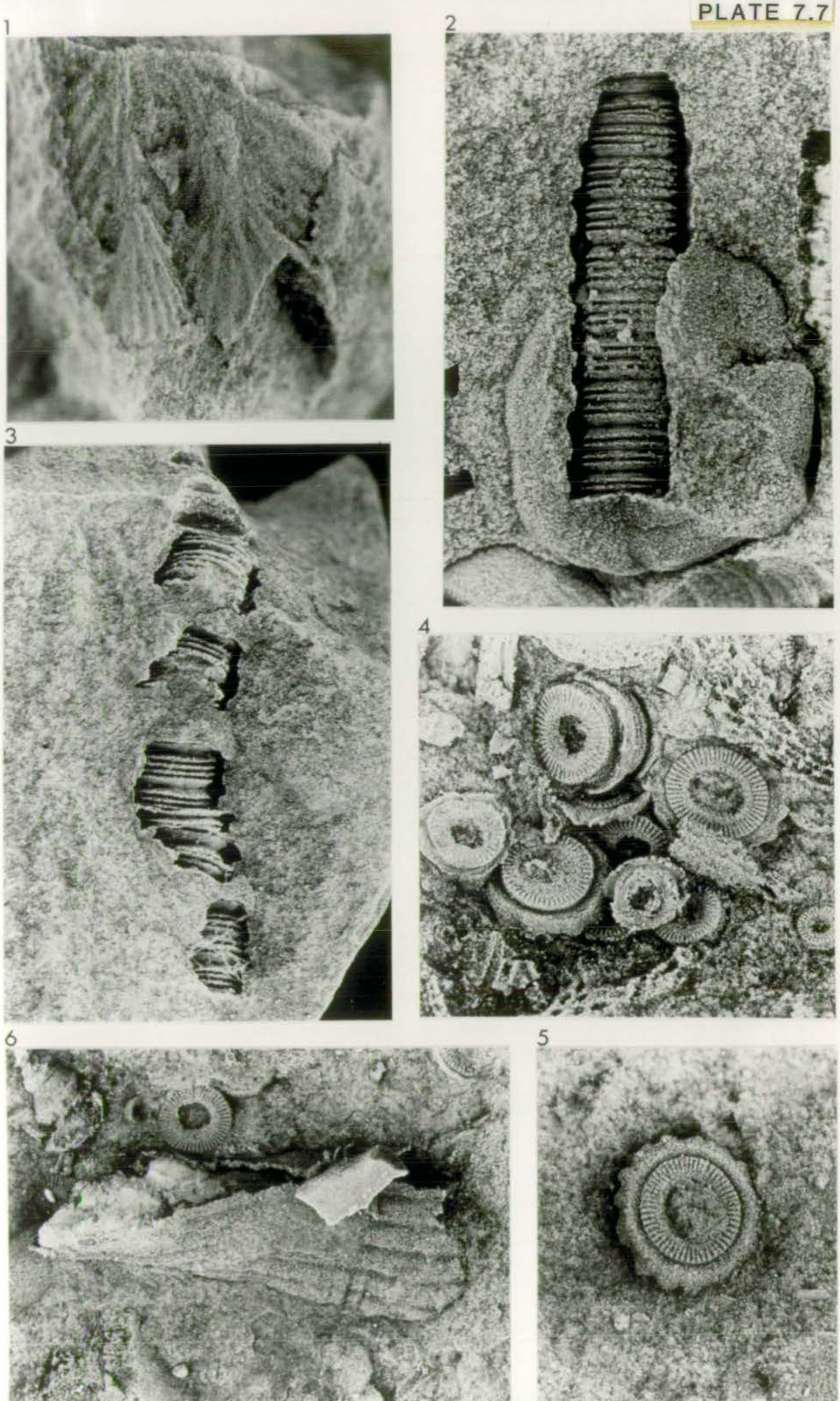


Plate 7.8

Trilobites

MULLOCH HILL FORMATION

Figures 1-4 *Calymene* (s.l.) *ubiquitosa* (Howells)

1. Internal mould, pygidium, TW.89.44 x 2.5
2. Internal mould, cranidium TW.89.45 x 3.5
3. Internal mould, cranidium TW.89.46 x 3.5
4. Internal, glabella, TW.89.47 x 3.5

Figure 5. *Astroproetus scoticus*

5. Internal mould, cranidium TW.89.48 x 4

Figures 6-7 *Acernaspis* cf. *elliptifrons* (Esmark)

6. Internal mould, cranidium, TW.89.49 x 3
7. Internal mould, pygidium, TW.57.50 x 4

PLATE 7.8

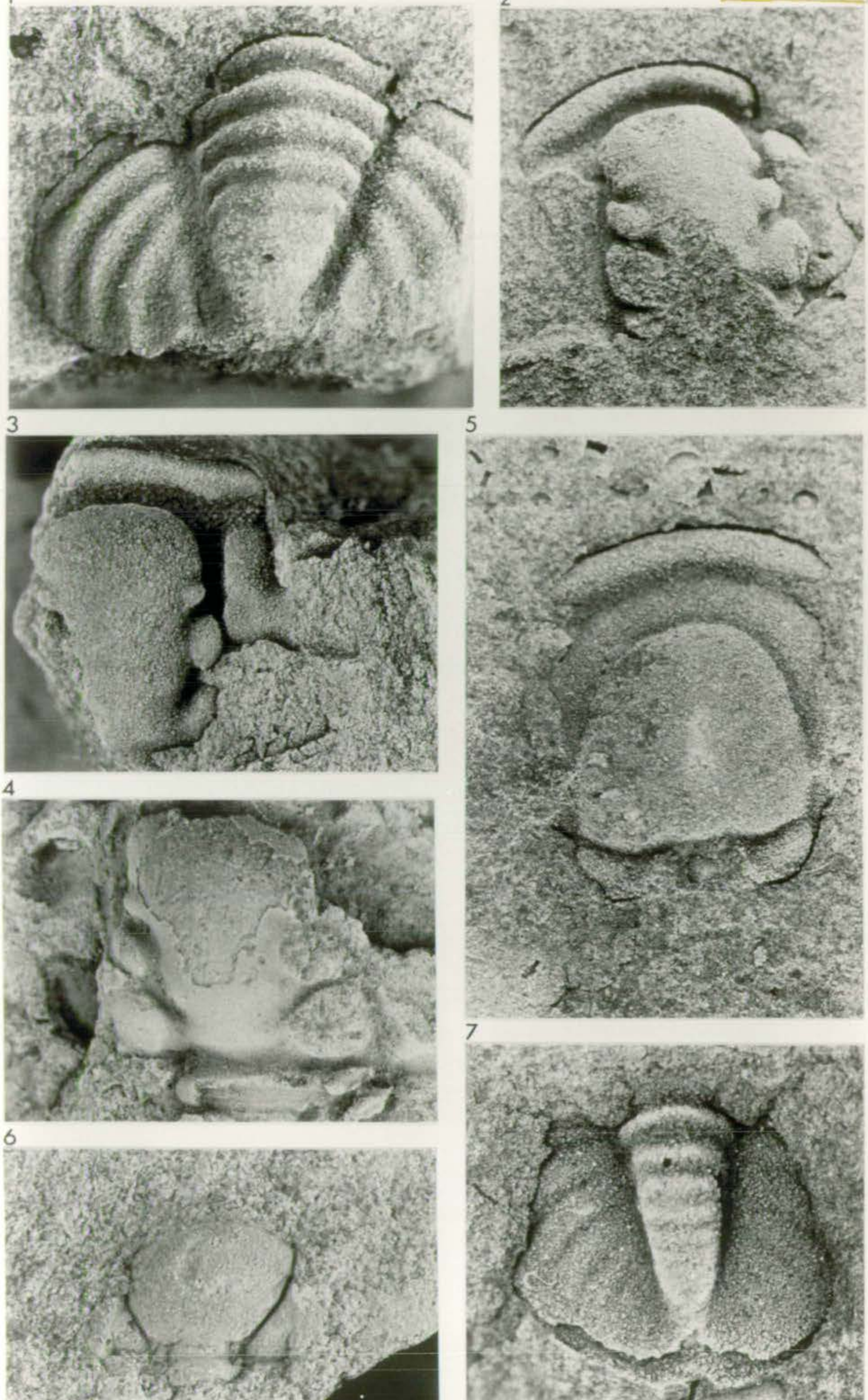


Plate 7.9

Ichnofossils

MULLOCH HILL FORMATION

Figures 1-4 Burrows

1. Lateral view of vertical burrow, TW.41.51a x 2.5
2. Lateral view of vertical burrow, TW.41.51 x 1
3. Lateral view of vertical burrow, TW.41.51b x 2.5
4. Thin section of vertical burrow, (Fig.3) MH.41 x 5

GLENWELLS SHALE

Figure 5 Burrows

5. Thin section view of burrows, GS1 x 4

WOODLAND FORMATION

Figure 6 Burrows

6. Thin section view of burrows, WF x 6

PLATE 7.9

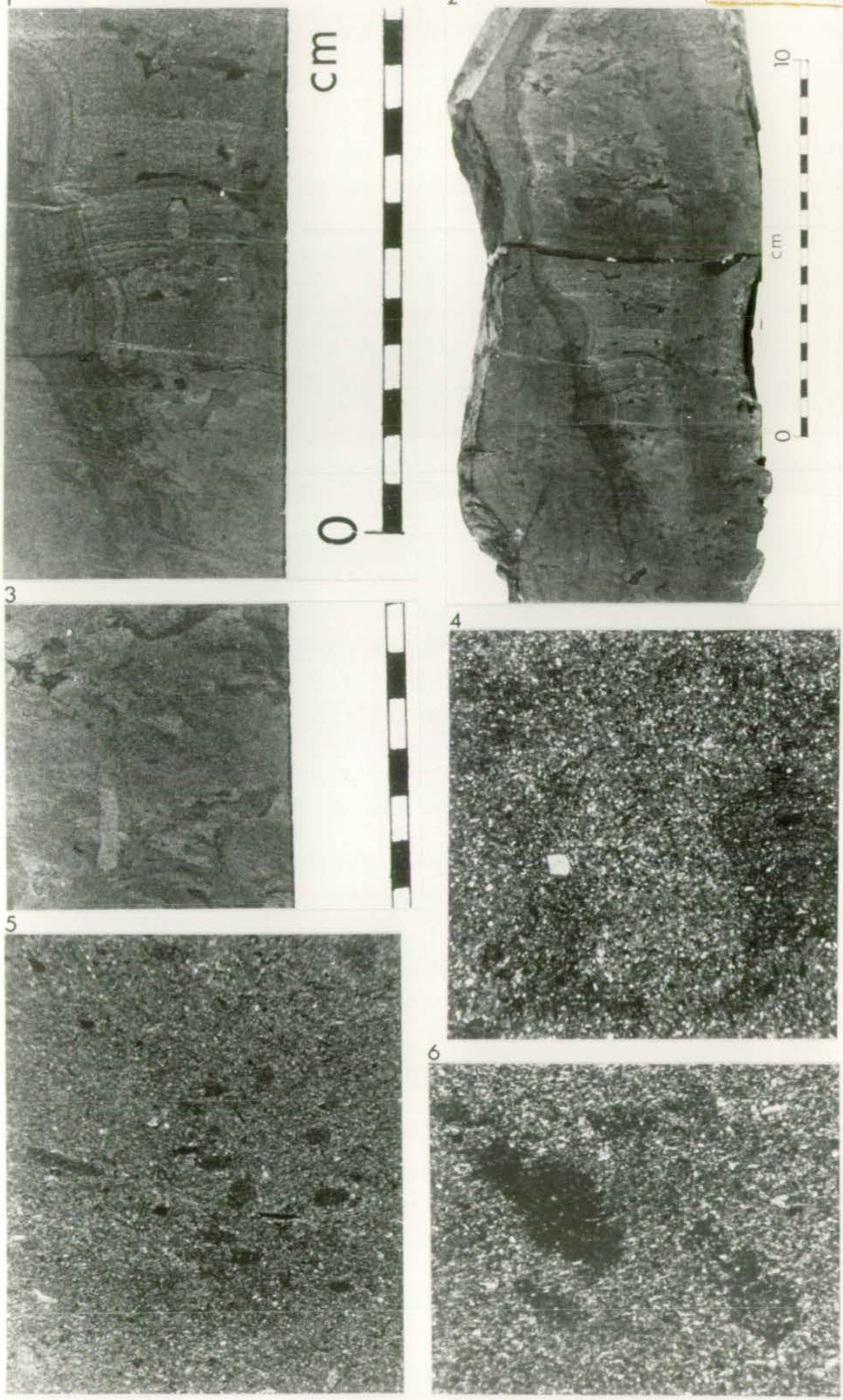


Plate 7.10

GLENWELLS SHALE FORMATION

Figure 1 *Rhagmophyllum crenulatus* McCoy

1. Apical view of corallite, TW.53.52 x 4

Figure 2 *?Nuculana curta* sp. nov.

2. Latex replica of exterior of right valve, TW.54.53 x 2.5

Figure 3 Bivalve fragment, ind.

3. Latex replica of exterior of left valve, TW.54.54 x 3

Figure 4 *Liospira ?simulans* (Salter)

4. Helicocone, external, dorsal view, TW.54.55 x 4

Figure 5 Camerate crinoid (possibly *Macrostylocrinus*)

5. Articulated arms, external, TW.52.56 x 4

Figure 6 Ostracod

6. Internal mould, TW.52.57 x 95.5X 5Kv

PLATE 7.10

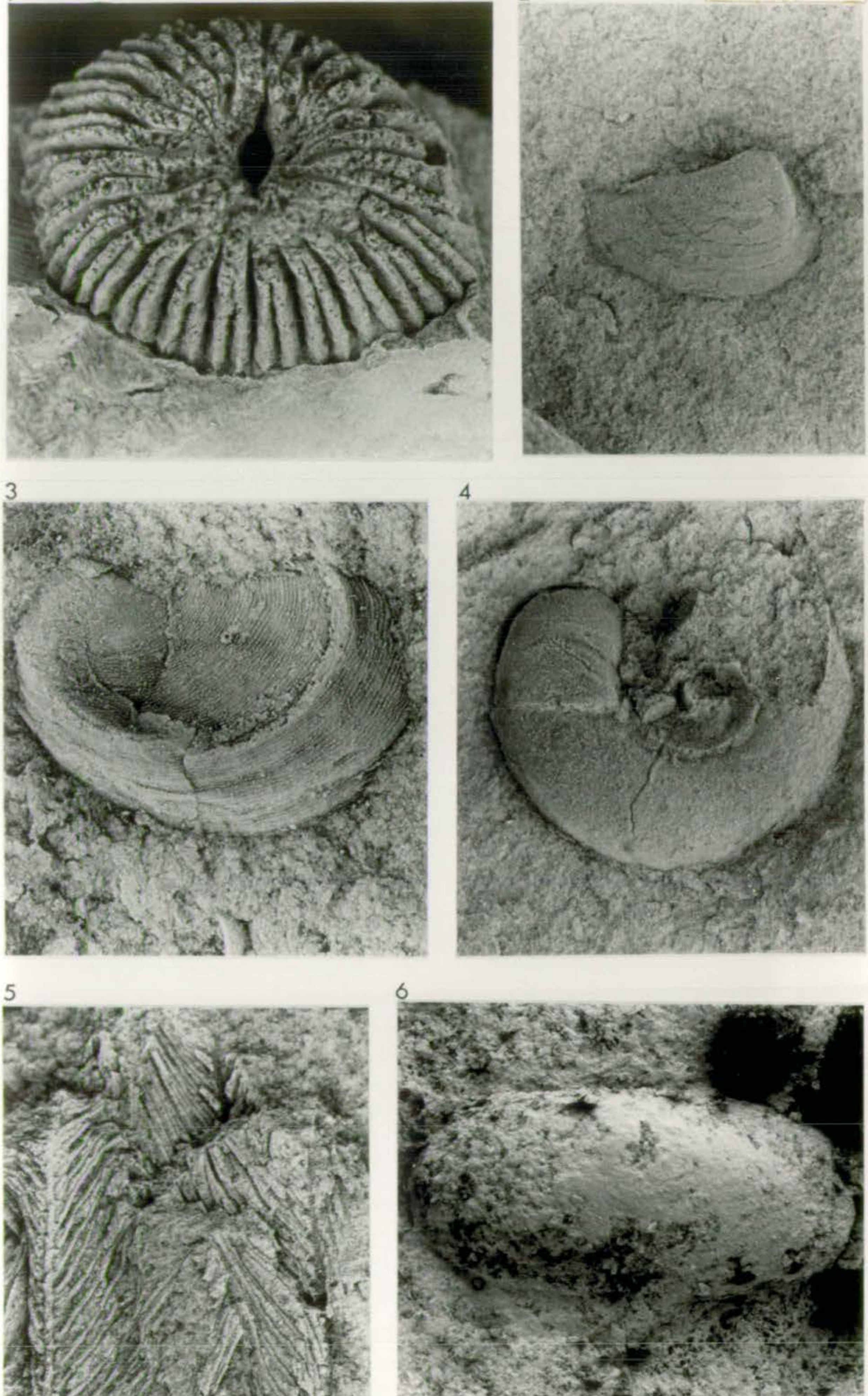


Plate 7.11

Brachiopods

GLENWELLS SHALE FORMATION

Figure 1 *Mendacella mullockiensis* (Davidson, 1869)

1. Internal mould of brachial valve, TW.52.58 x 3

Figures 2-4 *Eoplectodonta mullochensis* (Reed, 1917)

2. Latex replica of internal mould of pedicle valve, TW.52.59 x 3
3. Internal mould of pedicle valve, TW.52.59 x 3
4. Internal mould of pedicle valve, TW.52.60 x 4

Figure 5 *Leptaena* sp.

5. External mould of brachial valve, TW.52.61 x 2.5

Figure 6 *?Dolerorthis* sp.

6. Internal mould of pedicle valve, TW.52.62 x 2.5

Figure 7 *?Resserella* sp.

7. External mould of brachial valve, TW.52.63 x 2.5

Figure 8 *Atrypid* sp.

8. Internal mould of valve, TW.52.64 x 3

PLATE 7.11

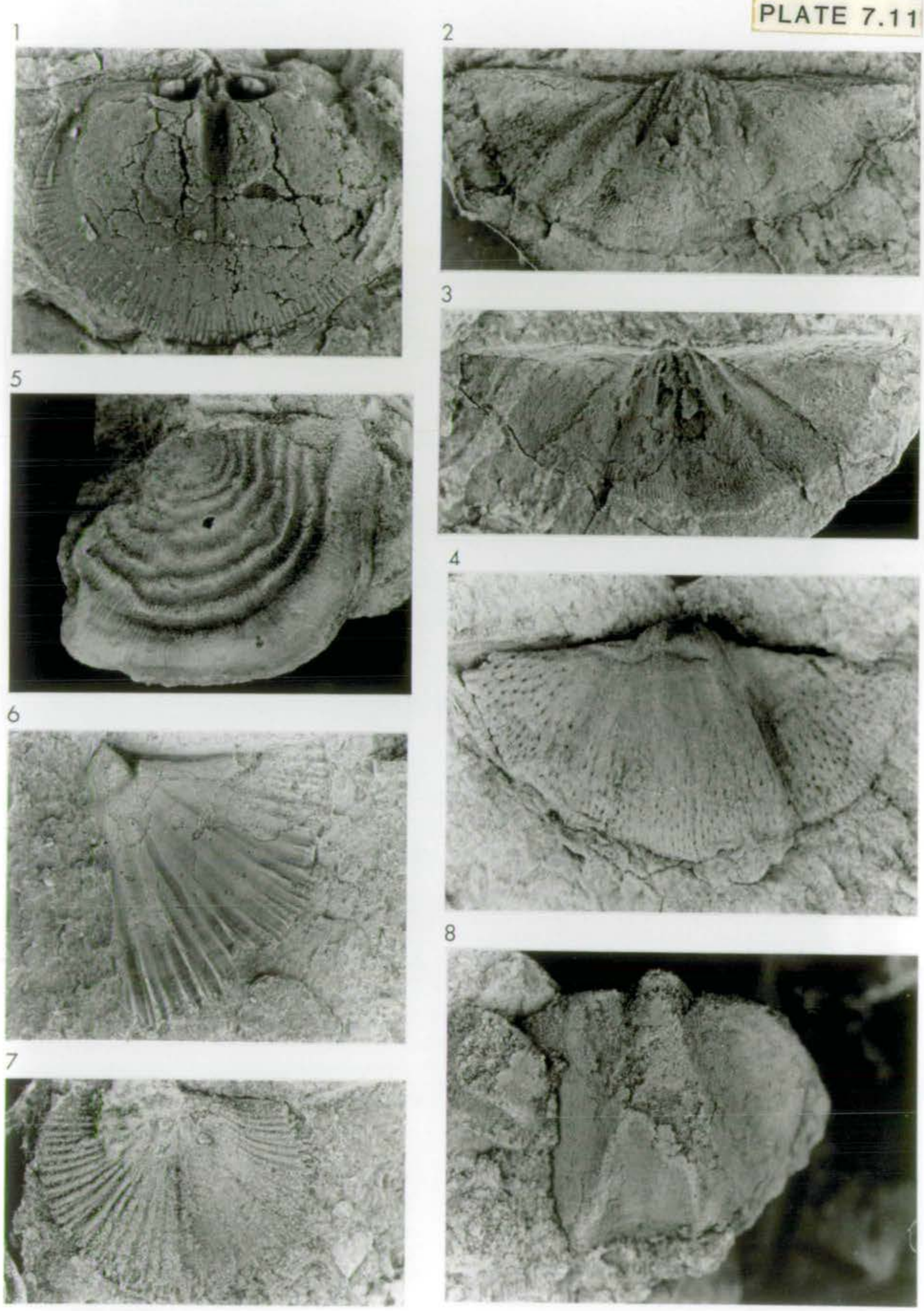


Plate 7.12

Trilobites

GLENWELLS SHALE FORMATION

Figures 1-2 *Platylichas scoticus* (Reed)

1. External mould of glabella, TW.52.65 x 3
2. Latex replica of external mould, glabella TW.52.65 x 3

Figures 3-5 *Encrinurus mullochensis* (Reed)

3. Latex replica of external mould, incomplete cranidium, TW.52.66 x 3
4. Internal mould of, incomplete cranidium, TW.52.67 x 3
5. Internal mould of pygidium, TW.52.68 x 4

Figure 6 *Stenopareia thomsoni* (Salter)

6. Internal, axis of thorax TW.52.69 x 4

Figure 7 *Ecrinurus mullochensis* (Reed)

7. Internal mould of pygidium, TW.52.70 x 4.5

Figure 8 *Calymene* (s.l.) *ubiquitosa* (Howells)

8. Internal mould of pygidium, TW.52.71 x 4

PLATE 7.12

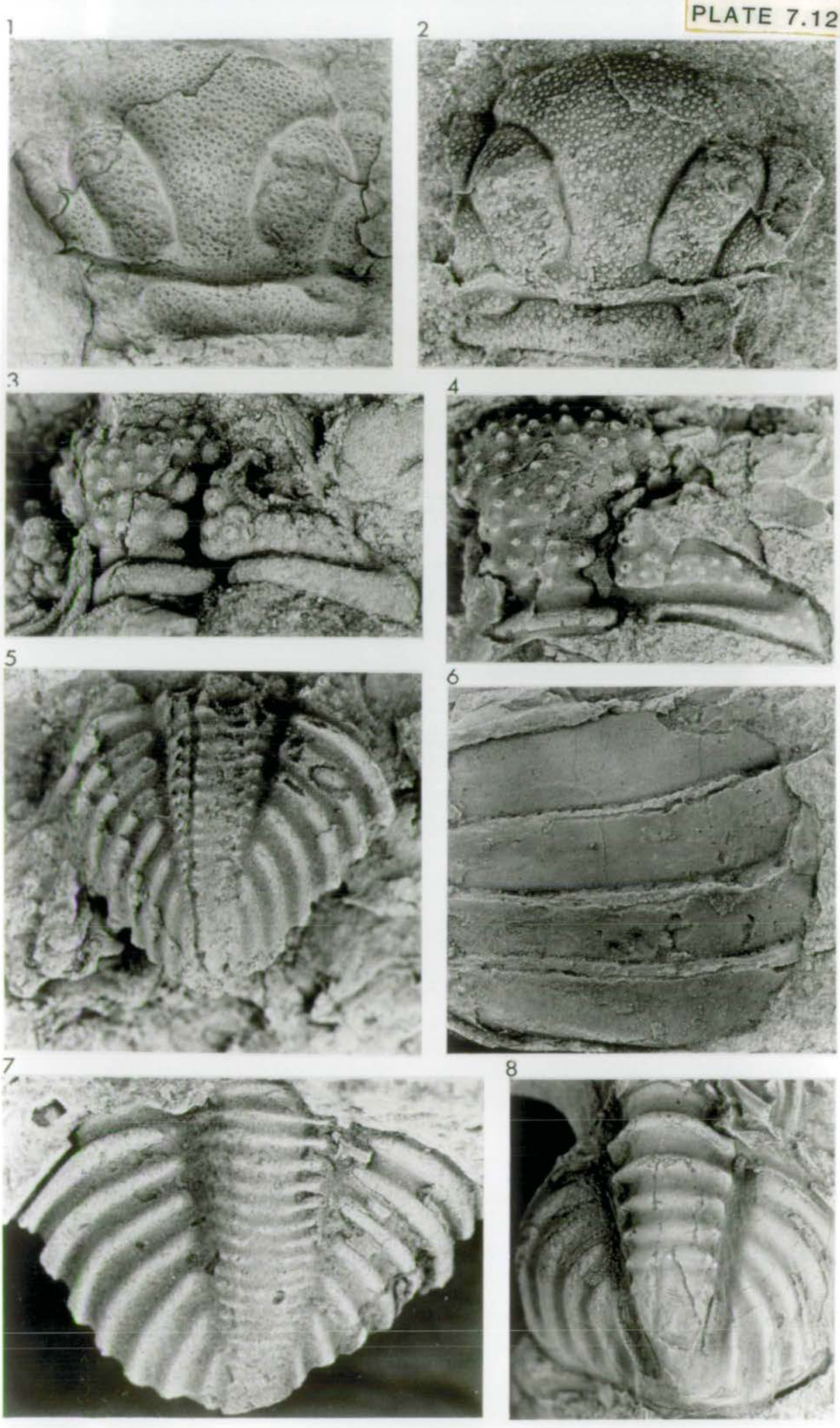


Plate 7.13

Graptoloids

GLENSHALLOCH SHALE FORMATION

Figures 1-2 *Monograptus triangulatus* (Harkness)

1. Lateral view of incomplete stipe, carbonised periderm, TW.129.72 x 10
2. Lateral view of incomplete stipe, carbonised periderm, TW.129.73 x 12

Figure 3 *Monograptus* cf. *atavus*

3. Lateral view of incomplete stipe, carbonised periderm, TW.129.74 x 10

Figures 4-5 cf. *Coronograptus gregarius*

4. Lateral view of incomplete stipe, carbonised periderm, TW.129.75 x 10
5. Lateral view of incomplete stipe, carbonised periderm, TW.129.76 x 12

Figure 6 *Rastrites* sp.

6. Lateral view of incomplete stipe, carbonised periderm, TW.129.77 x 7

Figure 7 *Climacograptus* sp.

7. Lateral view of incomplete stipe, carbonised periderm, TW.129.78 x 12

Figures 8-9 *Glyptograptus* sp.

8. Lateral view of incomplete stipe, carbonised periderm, TW.129.79 x 8
9. Lateral view of incomplete stipe, carbonised periderm, TW.129.80 x 14

Figures 10-11 *Climacograptus innotatus* sp. (Nicholson)

10. Lateral view of incomplete stipe, carbonised periderm, TW.129.81 x 16
11. Lateral view of incomplete stipe, carbonised periderm, TW.129.82 x 14

PLATE 7.13

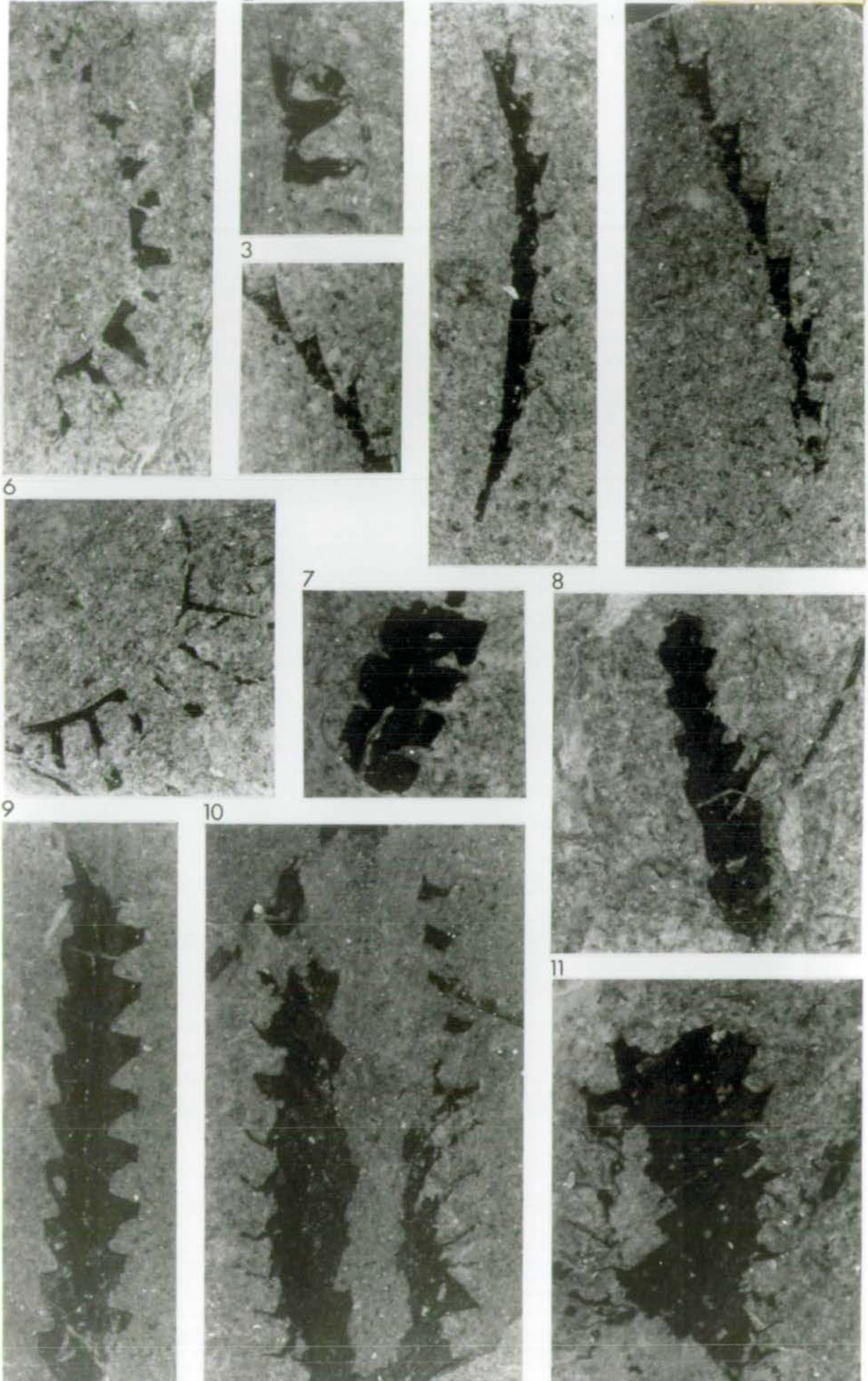


Plate 7.14

Graptoloids

WOODLAND FORMATION

Figures 1-3 *?Climacograptus gregarius*

1. Lateral view of incomplete stipe, carbonised periderm, TW.215.83 x 10

2. Lateral view of incomplete stipe, carbonised periderm, TW.215.84 x 8

3. Lateral view of incomplete stipe, carbonised periderm, TW.215.85 x 8

Figures 4-6 *?Glyptograptus* sp.

4. Lateral view of incomplete stipe, carbonised periderm, TW.215.86 x 5

5. Lateral view of incomplete stipe, carbonised periderm, TW.234.87 x 7

6. Lateral view of incomplete stipe, carbonised periderm, TW.234.88 x 5

Figures 7-8 *Climacograptus* cf. *wilsoni* (Lapworth)

7. Lateral view of incomplete stipe, carbonised periderm, TW.215.89 x 10

8. Lateral view of incomplete stipe, carbonised periderm, TW.215.90 x 14

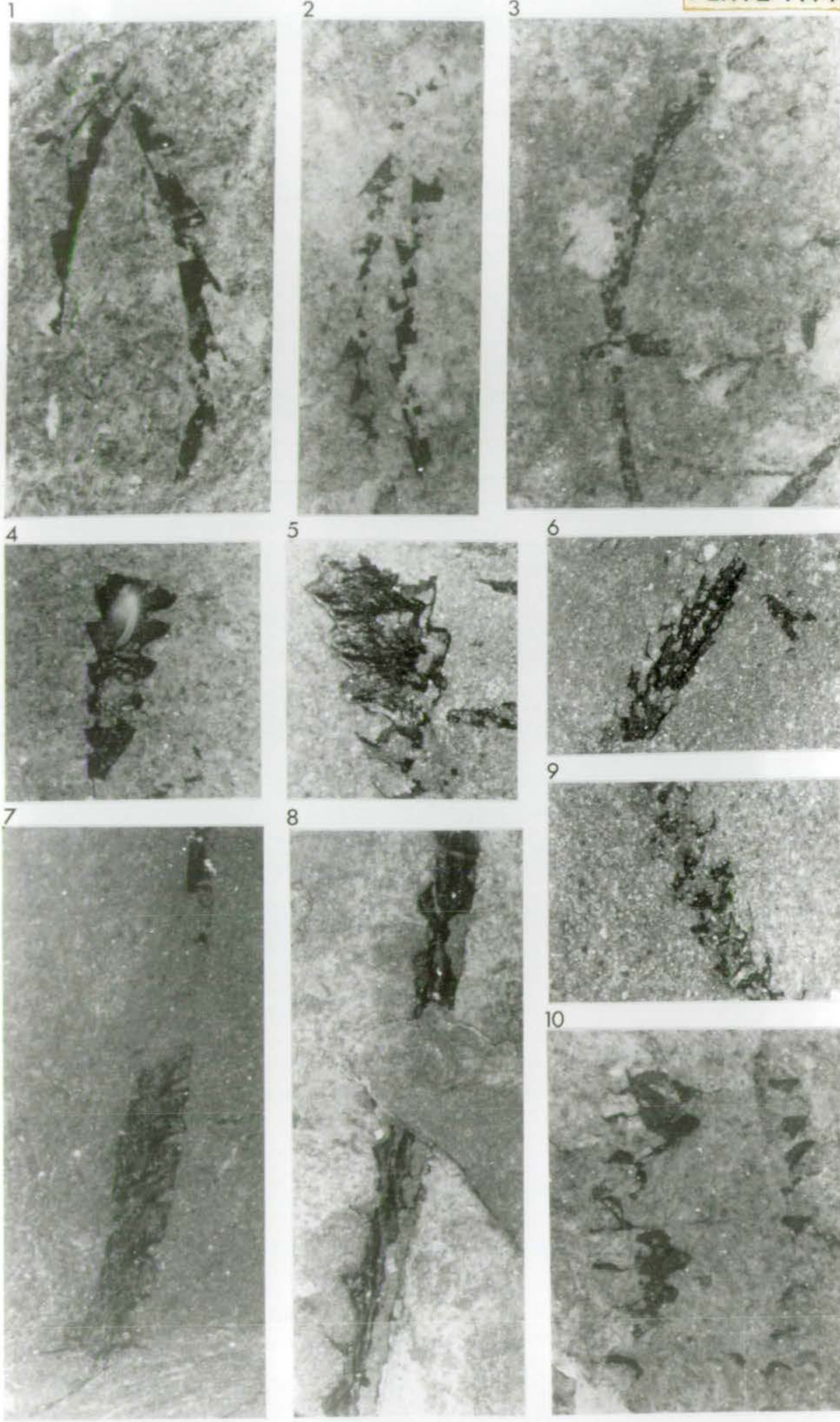
Figure 9 *?Glyptograptus* sp.

9. Lateral view of incomplete stipe, carbonised periderm, TW.215.91 x 5

Figure 10 cf. *Climacograptus innotatus* (Nicholson)

10. Lateral view of incomplete stipe, carbonised periderm, TW.234.92 x 10.

PLATE 7.14



CHAPTER 8

8 TAXONOMIC REVIEW OF THE BRACHIOPODS FROM THE MULLOCH HILL FORMATION, CRAIGHEAD INLIER

8.1 INTRODUCTION

With the exception of the trilobites (Howells, 1982) the Silurian fossils of Girvan remain generally in need of up-to-date taxonomic revision. In the present study it has proved possible only to review the taxonomy of the most common fossil taxa, ie. the brachiopods, from the Mulloch Hill Formation. Cocks (pers comm) is currently preparing a monograph of the brachiopods of the Newlands Formation. Description of other fossils, however, was limited by scarce specimens, poor preservation and by time, and as opposed to simply producing a list of fossil names, some of the other fossil taxa collected from the Craighead Inlier have been figured in Plates 7.1-7.14 Chapter 7, for illustrative purposes.

The following conventions are employed in the text:-

(?) - question marks, are used where there is any doubt as to the validity of the name given. For example, where there is doubt with respect to a particular specimen, the question mark occurs before the name, but a question mark after the name indicates doubt in the identification of the genus or species.

" " - quotation marks, around the genus or species, indicate that the name applied is used in the broadest sense.

aff. - affinities with, yet different from that genus or species

cf. - compares with and is closely related to the same genus or species.

The fossils illustrated in Plates 7.1 to 7.14 and Plates 8.1 to 8.10 are provisionally labelled TW.L.S; where 'L' represents the locality number and 'S' the specimen number, and are stored at the Grant Institute, Edinburgh University.

PHYLUM BRACHIOPODA (Dumeril, 1806)
Class INARTICULATA HUXLEY, 1869
Order *ACROTRETIDA* Kuhn, 1949
Suborder *CRANIIDINA* Waagen, 1885
Superfamily CRANIACEA Schuchert, 1896
Family CRANIIDAE Menke, 1828
Genus *PETROCRANIA* Raymond, 1911
Species *Petrocrania mullochensis* (Reed, 1917)

Class ARTICULATA Huxley, 1869

Order *ORTHIDA* Schuchert & Cooper, 1932

Suborder *ORTHIDINA* Schuchert & Cooper, 1932

Superfamily ORTHACEA Woodward, 1852

Family HESPERORTHIDAE Schuchert & Cooper, 1931

Subfamily DOLERORTHINAE Öpik, 1934

Genus *SCHIZONEMA* Foerste, 1909

Species *Schizonema subplicatum* (Reed, 1917)

Family RHIPIDOMELLIDAE Schuchert, 1913

Subfamily RHIPIDOMELLINAE Schuchert, 1913

Genus *MENDACELLA*

Species *Mendacella mullockiensis* (Davidson, 1869)

Order *DICTYONELLIDINA* Cooper, 1956

Superfamily EICHWALDIACEA Schuchert, 1893

Family EICHWALDIIDAE Schuchert, 1893

Genus *DICTYONELLA* Hall, 1868

Species *Dictyonella* sp.

Order *STROPHOMENIDA* Öpik, 1934

Suborder *STROPHOMENDIA* Öpik, 1934

Superfamily STROPHOMENACEA King, 1846

Family STROPHEODONTIDAE Caster, 1939

Subfamily STROPHEODONTINAE Caster, 1939

Genus *EOSTROPHEODONTA* Bancroft, 1949

Species *Eostropheodonta mullochensis* (Reed, 1917)

Family CHILIDIOPSIDAE Boucot, 1959

Genus *FARDENIA* Lamont, 1935

Species *Fardenia (Fardenia) columbana* (Reed, 1917)

Order *PENTAMERIDA* Schuchert & Cooper, 1931

Suborder *SYNTROPHIOIDEA* Ulrich & Cooper, 1936

Superfamily PORAMBONITACEA Davidson, 1853

Family STRICKLANDINIIDAE Hall & Clarke, 1894

Genus *STRICKLANDIA* Billings, 1859

Species *Stricklandia lens mullochensis* (Reed, 1917)

Order *RHYNCHONELLIDA* Kuhn, 1949
Superfamily RHYNCHONELLACEA Gray, 1848
Family OLIGORHYNCHIIDAE Cooper, 1956
Genus *RHYNCHOTRETA* Hall, 1879
Species *Rhynchotreta cuneata* (Dalman, 1828)

Family TRIGONIRHYNCHIDAE Maclaren, 1965
Genus *ROSTRICELLULA* Ulrich & Cooper, 1942
Species *Rostricellula mullochensis* (Reed, 1917)

Order *SPIRIFERIDAE* Waagen, 1883
Superfamily ATHYRACEA McCoy, 1884
Family MERISTELLIDAE Waagen, 1853
Genus *HYATTIDINA* Schuchert, 1913
Species *Hyattidina ? angustifrons* (Salter, 1851)

Family ATRYPIDAE Gill, 1871
Subfamily CLINTONELLINAE Cooper, 1977
Genus *ZYGOSPIRAELLA* Nikiforova, 1961
Species *Zygospiraella scotica* (Salter, 1851)

8.2 SYSTEMATIC DESCRIPTIONS

Class INARTICULATA Huxley, 1869
Order *ACROTRETIDA* Kuhn, 1949
Suborder CRANIDINA Waagen, 1885
Superfamily CRANIACEA Schuchert, 1896
Family CRANIIDAE Menke, 1828
Genus *PETROCRANIA* Raymond, 1911

Type species. By original designation *Philhedra (Philhedrella) mimetica* Kozowski, 1929, from the lower Devonian of Podolia, USSR.

Petrocrania mullochensis (Reed, 1917) Pl. 8.1, fig. 1.
1883 *Crania Siluriana* Davidson; Davidson, p215, pars, pl.17, figs 51-53, non figs 49,50.

1889 *Crania Siluriana* (Dav.), Peach & Horne p529.

1917 *Philhedra mullochensis* Reed, p822, pl.4, figs 30-33.

1968 *Philhedrella mullochensis* (Reed); Temple, p15.

Material, horizon and locality: 2 brachial valves from the Mulloch Hill Formation (Rhuddanian), Craighead, locality 89.

Diagnosis: Small, highly convex *Petrocrania* species, with a rounded conical profile; transversely subcircular. Ornamentation of delicate pustules, occasionally developing a few coarser, low rounded concentric rugae.

Remarks: The very poor preservation and consequential lack of internal structures hinders identification. The genus *Petrocrania* is used in the broadest sense.

Class ARTICULATA, Huxley, 1869

Order *ORTHIDA*, Schuchert & Cooper, 1932

Suborder *ORTHIDINA*, Schuchert & Cooper, 1932

Superfamily ORTHACEA Woodward, 1852

Family HESPERORTHIDAE Schuchert & Cooper, 1931

Subfamily DOLERORTHINAE Öpik, 1934

Genus *SCHIZONEMA* Foerste, 1909

Type species: By subsequent designation of Foerste 1912, p139 *Hebertella (Schizonema) fissistriata*. Foerste, 1909, from the Osgood Formation (Telychian) of Indiana, USA.

Schizonema subplicatum (Reed, 1917) Pl. 8.1, fig. 2.

1917 *Orthis calligramma* Dalman var. *subplicata* Reed, p828, pl.5, figs 10-15.

1949 *Orthis subplicata* var. *varicosa* Bancroft, p2, pl.1, figs 1-4.

1949 *Orthis subplicata* var. *neptuni* Bancroft, p3, pl.1, fig. 7.

1949 *Orthis subplicata* var. or mut. *felix* Bancroft, p3, pl.1, figs 5-6.

1951 *Schizoramma* cf. *subplicata* (Reed); Williams, p90, pl.3, figs 4-8.

1970 *Schizonema* sp. Temple, p17, pl.3, figs 17-18.

1978 *Schizonema subplicatum* (Reed, 1917); Cocks, p45.

1987 *Schizonema subplicatum* (Reed, 1917); Temple, p33, pl.2, figs 5-11.

Material, horizon and locality: 1 brachial valve and 1 pedicle valve from the Mulloch Hill Formation (Rhuddanian), Craighead, locality 78.

Diagnosis: Subquadrate *Schizonema* species of moderate convexity. Sharp narrow ribs, dying out towards umbo, separated by wide interspaces. Around peripheral commissure, the interspaces occasionally possess one or two very short thin ribs.

Remarks: The general shape, internal structures and distinctive ribbing of the pedicle valve, is indicative of *Schizonema*.

Originally Foerste (1909, p76-77) proposed the genus *Schizonema* although no type species was designated, but later he (1912, p.139) changed the name to *Schizoramma*, designating *Hebertella (Schizonema) fissistriata* Foerste, 1909 as the type species, and it is presumed that Foerste considered *Schizonema* Foerste, 1909 to be a homonym of *Schizonema* Agardh, 1824, (Bassett, 1970). However, *Schizonema* Agardh is a recent marine alga. Consequently, Bassett, 1970 employs *Schizonema* Foerste, 1909 as a senior objective synonym of *Schizoramma* Foerste, 1912.

Generally *Schizonema* has been assigned to the subfamily Hesperorthinae (e.g. see Schuchert & Cooper 1931, p243; 1932, p.85, and Williams, in Williams et al., 1965, p.H318, sic *Schizoramma*). Bassett (1970) points out that *Hesperorthis* and its close relatives such as *Barbarorthis* are characterised by having an antigydium in the notothyrium and an apical plate or modified deltidial plates in the deltidium, whereas *Schizonema* possesses an open delthyrium and notothyrium as does *Dolerorthis*. The only major difference between the latter two, is that *Schizonema* has accessory ridges lateral to the cardinal process. Therefore Bassett (1970) transferred *Schizonema* to the *Dolerorthinae*.

Order *ORTHIDA* Schuchert & Cooper, 1932
Suborder *ORTHIDINA* Schuchert & Cooper, 1932
Superfamily ORTHACEA Woodward, 1852
Family RHIPIDOMELLIDAE Schuchert, 1913
Subfamily RHIPIDOMELLINAE Schuchert, 1913
Genus *MENDACELLA*

Type species: By original designation *Orthis uberis* Billings, 1866, from the Ellis Bay Formation (Ashgill), Anticosti Island, Quebec, Canada

Mendacella mullockiensis (Davidson, 1869) Pl. 8.1, fig 3, pl.8.2 and pl.8.3.
1851 *Orthis reversa* Salter; Salter, p171, pl9, fig 13a-c.
1869 *Orthis reversa* Salter; Davidson, p220 pars, pl29, fig 13, non figs 11-12.
1869 *Orthis reversa* Salter var. Mullockiensis [Mullochiensis in plate explanation] Davidson, p221 pars, pl29, figs 14-17, non fig 18.

1882 *Orthis reversa* Lapworth, p625.

1883 *Orthis Mullockiensis* Davidson; Davidson p180, pl16, fig 14-15.

1899 *Orthis mullockiensis* (Dav), Peach & Horne, p529.

1917 *Orthis (Schizophorella) mullochensis* [sic] Davidson; Reed p859.

1940 *Mendacella mullochiensis* var. *crassiforms* Lamont, p28, fig 3, (1-3).

1949 *Mendacella crassiformis* Lamont; Bancroft, p5, pl1, fig 13.

1951 *Resserella llandoveriana* sp. nov. Williams, p96, pl1, fig 7-10.

1965 *Mendacella mullockiensis* (Davidson); Boucot et al, p336.

1970 *Resserella llandoveriana* Williams; Temple, p22, pl4, fig 1-6, pl5, figs 1-12.

1973 *Mendacella mullochiensis* Cocks & Toghill, p213.

1978 *Isorthis prima* Walmsley & Boucot, 1975; Cocks p69.

1983 *Mendacella sp.*; Lockley, p94, figs 2(3-7).

1984 '*Resserella*' sp.; Temple in Cocks et al p150, 152-4.

1987 *Mendacella mullockiensis* (Davidson, 1869) morph *mullockiensis*; Temple, p39, pl.4, figs 1-16.

Material, horizon and localities: 41 pedicle valves, 44 brachial valves from the Mulloch Hill Formation (Rhuddanian) localities 19, 74, 32 and 89.

Diagnosis: Unequally biconvex, subcircular shaped *Mendacella* species. Pedicle valve median depression extends for a short distance from the umbo. Brachial valve convex, with short wide fold. Ornamentation of thin irregularly spaced striations dying out before reaching the umbo. Deeply impressed musculature; ventral valve diductor tracks are elongated, subparallel or slightly divergent, rarely enclosing adductor scars, anteriorly, deep muscle scars, in dorsal valve divided longitudinally by wide mesial ridge. Small cardinal process.

Remarks: Originally this fossil was described in Davidson's Silurian monograph (1869) as *Orthis reversa*, Salter, but is distinguished there from the sulcus and fold in the brachial and pedicle valves. Reed (1917) pointed out that many of the shells which Davidson identified as *Orthis mullockiensis* in Mrs Gray's collection belong to *Isorthis amplificata* or other species but these are recognisable by their shape, and ribbing, and internally by the muscle scars and hinge structures.

In this study the orthids have been loosely grouped into *Mendacella*. However the *Mendacella* specimens show significant variation such as in the muscle fields of the brachial valve and possibly these can be further subdivided. The two species '*Isorthis amplificata*' (Walmsley, 1965) and '*Resserella canalis*' (J. de C Sowerby, 1839) seem to fall within the range of *M. mullockiensis*. These species can be differentiated by the shape of the adductor muscle scars since *Isorthis* adductor muscle scars are unequal in size, with the top pair of scars slightly larger and wider than the bottom pair. Conversely the top pair of adductor muscle scars in *Resserella* are slightly smaller and narrower, than the bottom pair. Furthermore, in *Isorthis*, the adductor scars are separated longitudinally by a medial ridge whereas in *Resserella*, the subellipitical adductor scars are separated by a broad axial ridge, which expands posteriorly producing a deep proximal sulcus.

Data is presented in graphical form in Appendix 4.1.

Order *DICTYONELLIDIAIA* Cooper, 1956
Superfamily EICHWALDIACEA Schuhert, 1893
Family EICHWALDIIDAE Schuhert, 1893
Genus *DICTYONELLA* Hall, 1868

Type species: *Atrypia corallifera* Hall, 1852, p281, pl58, figs 5a-1; from the Silurian (Niagaran, Wenlock-Ludlow of Lockport and Rochester, New York State, USA. By monotypy (Hall, 1868, p274).

Dictyonella sp. Pl. 8.1, figs 4, 5.

Material, horizon and locality: 1 incomplete valve, brachial?, from the Mulloch Hill Formation (Rhuddanian) Craighead, locality 41.

Diagenesis: Subtriangular to subcircular in outline. Ornamentation comprises a network of polygonal pits varying from rhombohedral, through hexagonal to subrounded, less than 0.5mm in diameter. Pits tend to be arranged in arcuate patterns.

Remarks: The specimen has the characteristic form and ornamentation of the genus *Dictyonella*, but is too fragmented to permit a species identification. The genus is recorded for the first time in the Mulloch Hill Formation.

Order *STROPHOMENIDA* Öpik, 1934
Suborder STROPHOMENIDA Öpik, 19345
Superfamily STROPHOMENACEA King, 1846
Family STROPHEODONTIDAE Caster, 1939
Subfamily STROPHEODONTINAE Caster, 1939
Genus *EOSTROPHEODONTA* Bancroft, 1949

Type species: By original designation, *Orthis hirnantensis* McCoy, 1851.

Eostropheodonta mullochensis (Reed, 1917) Pl. 8.4, figs 1-3.

1883 *Strophomena expansa* (J. de C. Sowerby); Davidson p194 pars, pl15, figs 1, 3-5, non fig 2.

1899 *Strophomena (Rafinesquina) expansa* (Sowerby), Peach & Horne, p530.

1917 *Stropheodonta (Leptostrophia) filosa* (Sowerby) var. *mullochensis* Reed, p894, pl17, figs 4-8.

non 1951 *Stropheodonta (Eostropheodonta) aff. mullochensis* [sic] Reed; Williams, p123, pl8, figs 1-4.

Material, horizon and localities: 1 pedicle valve and 2 brachial valves from the Mulloch Hill Formation (Rhuddanian) Mulloch Hill Quarry, (Rough Neuk Quarry), Locality 89, Craighead Inlier, Girvan, Strathclyde, NS270040.

Diagnosis: Large subquadrate *Eostropheodonta* species, slightly elongate anteriorly. Gently convex ventral value becoming flattened in the cardinal region. Dorsal valve slightly concave. Parvicostellate ribbing. Axial costae and immediately flanking costae, occasionally reach umbo. Equally spaced, equidimensional small pits present between ribs. Very faint triangular diductor muscle depressions in ventral valve. Muscle scars in brachial valve, weakly impressed, separated by low median ridge. Cardinal lobes elongated.

Remarks: *Eostropheodonta* can be distinguished from *Leptostrophia filosa*' (Sowerby), by the more pronounced subquadrate shape and absence of mucronate wings. Also, the characteristics of the internal structures differ from the similar shaped *Leptostrophia compressa*' (Sowerby).

Temple (1987) pointed out that *E. mullochensis* is clearly closely related to *E. multiradiata* Bancroft, 1949; pl2, fig 8; pl9, figs 1,4 from Fortune's Frolic, Haverfordwest, Dyfed. Biometric comparison is hindered due to the poor preservation and large size of the Welsh form. Data is presented in graphical form in Appendix 4.2.

Family CHILIDIOPSIDAE Boucot, 1959

Genus *FARDENIA* Lamont, 1935

Type species: By original designation, *Fardenia scotica* Lamont, 1935 from the Quarrel Hill Formation (Cautleyan), Drummuck Group, Girvan.

Fardenia (Fardenia) columbana (Reed, 1917) Pl. 8.5, figs 1-6.

1917 *Stropheodonta (Brachyprion) columbana* Reed, p896, pl17, figs 13-19.

1949 *Fardenia columbana* (Reed); Bancroft, p9.

Material, horizon and localities: 2 pedicle valves and 7 brachial valves from the Mulloch Hill Formation (Rhuddanian), Craighead, localities 19, 32 and 89.

Diagnosis: Large, subquadrate *Fardenia* species, almost as long as wide. Unequally biconvex. Brachial valve more uniformally convex, occasionally developing a wide weak median depression. Parvicostellate ornamentation. Costae have higher relief, twice as wide as costellae. Ventral crural fossettes present on inner region of dental plates. Short ridges lying in front of delthyral chamber. Stout dorsal cardinal process flanked by arched chilidial plates. Deep grooves may develop in posterior face. Small median tubercle situated in front of cardinal process.

Remarks: Williams (in Williams et al 1965, pH407) placed *Coolinia* and *Chilidiopsis* in synonymy with *Fardenia* Lamont, 1935 (type species *F. scotica* Lamont, 1935) and commented that the childium was variable. Bassett (1974) however argued that *F. scotica* possesses small, discrete chilidial plates and these characteristic features can be used to separate the species generically from *Coolinia.* Specimens found in the Mulloch Hill Formation displaying these small, chilidial plates, verify this.
Data is presented in graphical form in Appendix 4.3.

Order *PENTAMERIDA* Schuchert & Cooper, 1931
Suborder SYNTHROPHIOIDEA Ulrich & Cooper, 1936
Superfamily PORAMBONITACEA Davidson, 1853
Genus *STRICKLANDIA* Billings, 1859

Type species: By subsequent designation of Oehlert 1887, p131D, *Atrypa lens* J. de C. Sowerby, 1839.

Type specimen: Lectotype of *mullochensis*, selected Cocks (1978); B72 462; a brachial valve, the original of Reed 1917, p123, fig. 5 from the Mulloch Hill Formation (Rhuddanian), Mulloch Hill Quarry (Rough Neuk Quarry), Craighead Inlier, Girvan, Strathclyde. NS270040.

Stricklanida lens mullochensis (Reed, 1917) Pl. 8.6, figs 1-6.
1917 *Stricklandia mullochensis* sp. nov. Reed, p932, pl.23, figs 5-8.
1951 *Stricklandia lens* (J. de C. Sowerby) *prima* subsp. nov. Williams; p99, pl.4, figs 19-20.
1966 *Stricklandia lens prima* Williams; Amsden, p1013, pl.116, figs 1-7.
1978 *Stricklandia lens prima* Williams; 1951, Cocks p141.

?1982 *Stricklandia lens prima* Williams; Baarli & Johnson, pl.1, figs 1-3.

1984 *Stricklandia lens* (J. de C. Sowerby, 1839); Temple in Cocks et al [pars] table 4.

?1986 *Stricklandia lens prima* Williams; Baarli, p121, figs 1-2.

1987 *Stricklandia lens mullochiensis* (Reed, 1917); Temple p98, pl.11, figs 1-4.

Material, horizon and locality: 3 pedicle valve, and 1 brachial valve from the Mulloch Hill Formation (Rhuddanian), Craighead, loose fragment found near Mossgennoch Wood, locality 115.

Diagnosis: Subcircular to elongate shaped *Stricklandia* species; with a smooth shell surface of moderate convexity. Broad shallow ventral median depression, disappears beyond the umbo.

Remarks: Although these specimens are poorly preserved the internal structures of the pedicle valve, such as incurved, small elongated interarea, and open delthyrium are characteristic of the genus *Stricklandia*. The author considers *S.l. prima* to be a junior synoymn of *S.l. mullochensis*

Order *RHYNCHONELLIDA* Kuhn, 1949

Superfamily RHYNCHONELLACEA Gray, 1848

Family OLIGORHYNCHIDAE Cooper, 1956

Genus *RHYNCHOTRETA* Hall, 1879

Type species: By original designation, *Terebratula cuneata*, 1828 (see below).

Rhynchotreta cuneata (Dalman, 1828) Pl. 8.7, fig. 1.

1828 *Terebratula cuneata* Dalman, p141, pl.6, figs 3a-c.

1828 *Terebratula cuneata* Hisinger, p220, pl.6, fig. 5.

1839 *Terebratula cuneata* Dalman; J. de C. Sowerby in Murchison, p625, pl.12, fig. 13.

1867 *Rhynchonella cuneata* (Dalman & Hisinger); Davidson, p164, pl.21, figs 7-16, non fig. 12.

1882 *Rhynchonella cuneata* (Dalman); Lapworth, p625.

1883 *Ryhnchonella cuneata* (Dalman & Hisinger); Davidson p152, pl.10, fig. 1, non figs 9-10.

1899 *Rhynchonella cuneata* (Dalman); Peach & Horne, p529.

1937 *Rhynchotreta cuneata* (Dalman); St Joseph, p161.

1971 *Rhynchotreta cuneata* (Dalman) var; Reed, p942, pl.XXIV, fig. 18.

1974 *Rhynchotreta cuneata* (Dalman); Bassett & Cocks, p25, pl.8, fig. 1.

Material, horizon and locality: 2 pedicle valves from the Mulloch Hill Formation (Rhuddanian), locality 89.

Diagnosis: Small, oval to subtriangular *Rhynchotreta* species with strong, low rounded rib ornament. Median septum in pedicle valve, extends half its length and is surrounded on each side by 8-9 ribs curving slightly outwards, producing a crenulated posterior commissure.

Remarks: The two pedicle valves are so referred because of their shell shape, and ornamentation. Reed (1971) has pointed out that as compared to Davidson's specimens (1867), the Girvan examples generally are not markedly sulcate, tending to have flatter shells and longer, straighter hinge lines. In addition there is a great deal of variation in the number and coarseness of ribs.

Family TRIGONIRHYNCHIDAE MacLaren, 1965

Genus *ROSTRICELLULA* Ulrich & Cooper, 1942

Type species: By original designation *Rostricellula rostrata* Ulrich & Cooper, 1942 from the Wardell Formation (Caradoc) of Tennessee, USA.

Rostricellula mullochensis (Reed, 1917) Pl. 8.7, figs 2-8.

1917 *Rhynchospira (Homoeospira) Bouchardi* (Davidson) var. *mullochensis* Reed, p951, p124, figs 44-45, ?fig. 46.

Lectotype: Selected by Cocks (1978); B723303; conjoined valves, the original of Reed 1917, p124, fig. 44 from Mulloch Hill Formation (Rhuddanian), Mulloch Hill Quarry (Rough Neuk Quarry), Girvan, Strathclyde NS 270040.

Material, horizon and localities: 2 pedicle valves, and 2 brachial valves from the Mulloch Hill Formation (Rhuddanian) localities 19 and 32.

Diagnosis: Small subtriangular to elongate *Rostricellula* species; inequivalve, unequally biconvex; convexity of brachial valve is slightly greater than that of the pedicle valve. Ornamentation of sharp, low, parallel-sided ribs becoming stronger and slightly thicker anteriorly. Crenulated anterior commissure. Between 6-8 ribs closely flank median, become slightly curved outwards. Ventral beak high, directed forward and slightly incurved. Central region forms an anteriorly expanding depression with a variably developed axial sulcus in the anterior of the commissure.

Remarks: Reed's (1917) generic classification of *Rostricellula mullochensis* is based upon two small complete specimens, and two small pedicle valves. A large topotype population collected by Cocks and Toghill (1973) confirms the allocation of *mullochensis* to *Rostricellula*. Temple (1987) has pointed out further study may show the specimens to be related closely to Meifod specimens of *Rhynchotreta* sp. - as both have similar outlines, possess small sulcus and faint linear cardinal processes.

Order *SPIRIFERIDAE* Waagen, 1883

Superfamily ATHYRACEA Gill, 1871

Family MERISTELLIDAE Waagen, 1883

Genus *HYATTIDINAE* Schuchert, 1913

Type species: Original designation. *Atrypa congesta* Conrad, 1842, p265, from the Clinton Formation (late Llandovery) of New York State, USA.

Hyattidina ?angustifrons (Salter, 1851) Pl. 8.8, figs 1-6, pl.8.9, figs 1-6.

1851 *Hemithyris angustifrons* [McCoy MS] Salter, P171, pl9, fig 10a, b.

1851 *Hemithyris angustifrons* McCoy, p391.

1852 *Hemithyris angustifrons* (McCoy), McCoy, p199, pl1H, fig 6-8.

1882 *Meristella angustifrons* Lapworth p625.

1899 *Meristella angustifrons* (McCoy), Peach & Horne, P529.

1917 *Whitfieldella angustifrons* (McCoy), Reed, p953, pl.XXIV, fig 50-52.

1935 *Meristina mullochensis* Reed, p10, pl1, fig 9, 9a.

1973 *Cryptothyrella angustifrons* Salter; Cocks & Toghill, p213.

1978 *Cryptothyrella angustifrons* (Salter, 1851); Cocks, p164.

1983 *Cryptothyrella angustifrons* (Salter); Lockley, p94, figs 2, (12-15) *[=C.crassa]*.

1984 *Cryptothyrella angustifrons* (Salter, 1851); Temple in Cocks et al, p150, fig 25.

1987 *Hyattidina ?angustifrons* (Salter, 1851); Temple p121, pl.15, figs 1-13.

Material, horizon and localities: 57 conjoined valves, 105 pedicle valves and 114 brachial valves, principally from the Mulloch Hill formation (Rhuddanian) localities 19, 32, 89.

Diagnosis: Unequally biconvex *Hyattidina* species with an ovate to elongate shape. Occasionally very gentle ventral sulcus and dorsal fold developed. Deeply impressed musculature; muscle scar begins in front of pedicle chamber, widening rapidly anteriority; dorsal valve adductor scars form narrow track expanding, then contracting anteriorly, with an axial ridge flanked by paired grooves and ridges. Open notothyrium with two triangular sockets separated by thin median slit. Smooth shell surface, occasionally marked with concentric growth lines.

Remarks: Numerically this species is the most dominant brachiopod within the Mulloch Hill Formation and throughout the Formation it shows considerable variation in dimensions and the development of the myophragms.

Cocks (1973) identified this as *Cryptothyrella angustifrons*, but it differs from this species in various respects.

In *Hyattidina*, the dental plate ridges are shorter, tending not to develop such a distinctive raised platform contrasting with the dental plates of *Cryptothyrella*, which extend beyond the pedicle chamber bounding the muscle field pastro laterally and are striated with furrows or more longitudinal grooves. The umbo in *Hyattidina* overhangs to a lesser degree than in *Cryptothyrella*.

In the brachial valve, the sockets are more triangulate and the hinge line is straight as opposed to the u-shaped hinge line of *Cryptothyrella* (from which long, median septum extends as a low ridge along the length of the shell). Furthermore *Hyattidina* has two distinct narrow elongated parallel ridges separated by a mantle canal in the centre, extending between one-third and a half of the distance to the anterior margin.

Based upon this evidence, it does appear that formerly this species has been incorrectly identified and in fact the specimens should be assigned to *Hyattidina*.

Temple (1987) has pointed out that Welsh specimens differ from the Mulloch Hill samples in their smaller mean size and also differ in shape. He investigated the geographical differences in shape, between the various samples referred to *angustifrons*, using discriminant function analysis. The results show that the Welsh specimens have longer pedicle chambers, lower platforms, and shorter, more widely separated dental plates. Data is presented in graphical form in Appendix 4.4.

Family ATRYPIDAE Gill, 1871
Subfamily CLINTONELLINAE Copper, 1977
Genus *ZYGOSPIRAELLA* Nikiforova, 1961

Type species: By original designation, *Terebratula duboisi* Verneuil, 1845, from the Juuri Horizon (Rhuddanian of Estonia, USSR).

Zygospiraella scotica (Salter, 1851) Pl. 8.10, figs 1-6.

1851 *Hemithyris scotica* [McCoy MSS] Salter, p171, pl9, figs 12a-c.

1852 *Hemithyris hemisphaerica* (J. de C. Sowerby) *scotica* McCoy; McCoy in Sedgwick and McCoy, p202, pl1H, fig 10.

1867 *Atrypa? scotica* (McCoy); Davidson, p140, pl13, figs 31, 31a, b.

1882 *Atrypa hemisphaerica* (McCoy); Lapworth, p625.

1899 *Atrypa scotica* (McCoy); Peach & Horne, p529.

1917 *Coelospira scotica* (McCoy); Reed, p956, pars, non pl24, figs 56-58.

1973 *Coelospira scotica* (McCoy); Cocks & Toghill, p213.
1978 *Zygospiraella scotica* (Salter, 1851), Cocks, p159.

Material, horizon and localities: 89 pedicle valves and 42 brachial valves from the Mulloch Hill Formation, Rhuddanian, localities 19, 74, 32, 89.

Diagnosis: Unequally biconvex, subquadrate *Zygospiraella* species. Small, narrow, strong ribbing, usually bifurcated, up to 25 per valve. Concentric growth lines crenulated anteriorly. Small shallow median sinus in dorsal valve, and corresponding pedicle fold, marked by deeper grooves on each side.

Remarks: The specimen has the characteristic form and ornamentation of *Z. scotica*. Data is presented in graphical form in Appendix 4.5.

8.3 CHANGES IN THE FAUNAL COMPOSITION THROUGH THE ORDOVICIAN-SILURIAN JUNCTION, CRAIGHEAD

Within the Girvan district, an almost stratigraphically complete series through the Ordovician-Silurian junction is afforded by the Craighead Inlier. Marking this junction there is a noticeable change in the brachiopod faunal composition; and the relatively diverse *Hirnantia* fauna of the Ordovician High Mains Formation is replaced by a *Hyattidina* fauna in the succeeding Silurian Mulloch Hill Conglomerate.

As stated previously the Ordovician-Silurian junction in the Girvan district is represented by an unconformity, where the basal Silurian rocks both overstep and overlap the Upper Ordovician strata south and southwestwards. The junction in Craighead, although not clearly exposed is assumed to be fairly sharp with a slight angular discordance. Here many of the earlier Silurian brachiopod faunas have congeners in the underlying Ordovician strata (Harper, 1988).

8.3.1 High Mains Formation (Ordovician)

In the Craighead Inlier the highest Ordovician strata are represented by the High Mains Formation, exposed in the vicinity of High Mains Farm. Lithologically it is characterised by grey-green, fine to medium-grained, thinly and thickly bedded sandstones. Sedimentary structures are generally lacking although shelly horizons are developed at various levels. Harper (1981) has identified thirteen different brachiopod species dominated by *Hirnantia sagittifera* (McCoy), *Eostropheodonta* aff. *hirnantensis* (McCoy) and *Hindella crassa* (J de C. Sowerby) *incipiens* (Williams) which designate an Ordovician *Hirnantia* fauna. However, the brachiopod fauna is infiltrated with species of *Glyptorthis*, *Plaesiomys*, *Platystrophia*, *Eochonetes*, *Eopholidostrophia, Fardenia, Rostricellula, Hypsitycha* and *Eospirigerina*. Apart from *Hypsitycha* all these species have affinities in the underlying Drummuck Group. In addition Owen (1986) has recognised five trilobite taxa.

Deposition of the High Mains Formation occurred in channels, developing on deep parts of the shelf and upper parts of the slope. Changes in grain size, bedding and faunal composition indicate a minor regression (Harper, 1988). Possibly this period of regression was a response to the glacio-eustatic event, occurring near the end of the Ordovician (Brenchley & Newall, 1980). Yet additional tectonic controls are invoked by Harper (1988) because the regression in the Girvan district would require a fall in sea level, in excess of 50-100m estimated by Brenchley & Newall (1980). The glaciation led to the cooling of surface waters and to the drainage of the broad continental shelves which was accompanied by a rapid rise in sea level at the beginning of the Llandovery (Sheehan, 1977).

8.3.2 Mulloch Hill Formation

Overlying the High Mains Formation, the Mulloch Hill Conglomerate Formation represents the lowest part of the Silurian. A very low diversity fauna is found in the middle member of the Formation, characterised by medium-grained thinly bedded lithic arenites. The fauna is dominated by *Hyattidina ?angustifrons* (Salter) with species of rhynchonellids, dalmanellids, *Fardenia, Leptaena* and *Lingula* (Fig 8.1a and b). Disarticulated crinoid ossicles are also abundant whilst gastropods are scarce. As discussed in chapter 2 the sediments and fauna indicate deposition in shallow shelf condition and the gradual infilling of an erosional channel system. Harper (1979) discloses that both species of *Hyattidina* (Salter) and *Rhynchotreta* (Cocks & Toghill, 1973) have almost identical relatives in the fauna of the upper Rawtheyan Ladyburn Starfish beds, which are typical of shallow water environments originating during the early Llandovery global transgression (Sheehan, 1977).

Taking into consideration the changes in the faunal succession through the Ordovician-Silurian in the Craighead Inlier, Harper (1988) recognises 3 distinct phases in its development: (1) above the Rawtheyan to *Hirnantia* boundary, there is a significant decrease in the brachiopod taxa, dominated by an Hirnantian fauna but this characteristic fauna is diluted with elements of middle Ashgill brachiopods, originating from the North American province (Harper, 1988); (2) early to middle Rhuddanian times, when there was a low diversity fauna characteristic of the then, recently colonised shallow water environments in the North American province; (3) middle to late Rhuddianian times, when the diversity of the fauna increased considerably. (Both phase 1 and 2 are concomitant with channel development during regression).

Bretsky and Lorenz's (1970) model accords with the gradual reduction in species diversity in phase 1. During the Late Ordovician, some faunal elements may have been unable to cope with the deterioration of the environmental stability, caused by the gradual shrinkage of the habitat, when sea levels were low.

The resulting low diversity fauna (phase 2), may be attributed to a combination of colonisation after an ecological disaster, and the subsequent creation of a 'new' environment which was as yet relatively unstable and unpredictable (Slobodkin & Sanders, 1969). Clearly, whilst the pebbles and cobbles of the Mulloch Hill Conglomerate were being deposited the conditions were very inhospitable and unfavourable for the re-population of the substratum.

Gradually with the development of a more beneficial environment, the surroundings became more suitable for colonisation by a tolerant fauna and in conjunction the fauna increased in diversity with the number of brachiopod species rising from six (in the Mulloch Hill Conglomerate) to in excess of eleven in the Mulloch Hill Formation (Fig 8.1). This is attributed to the Llandovery transgression which followed the regression.

Although *Hyattidina* is dominant and often occurs exclusively in fossil horizons, it is not considered to be an opportunistic species. Grassle and Grassle (1974) specify that opportunistic species are the first taxa to occupy an area following a major crisis that eliminated an earlier fauna. Such species would occur only as the first stage in a succession of faunas. Normally the species would be limited to a narrower niche, but the form has the genotypic capability of occupying a far broader environmental spectrum, than is normally the case if outside competition is removed by a catastrophe. The appearance of *Hyattidina* is not, however, followed by a regular succession of other faunas back to a normal community, but this genus remains dominant throughout the Formation. Thus the high numerical dominance and the low diversity of the *Hyattidina* horizons is not indicative of an opportunist, but suggests that *Hyattidina* was a pioneer species which could adapt itself to the prevailing unstable conditions.

As well as an increase in brachiopod species, there was also an increase in the number of other phyla from five in the Mulloch Hill Conglomerate to fourteen in the Mulloch Hill Formation (Fig 7.1).

8.3.3 Oslo Region, Norway

Comparisons may be drawn with the Oslo Basin boundary section where relict Ordovician taxa are not displaced by more typical Silurian elements until at least the middle Rhuddanian (Baarli & Harper, 1986). It should be pointed out, however, that the section there is more complete and stable. Whereas it was the trilobites,

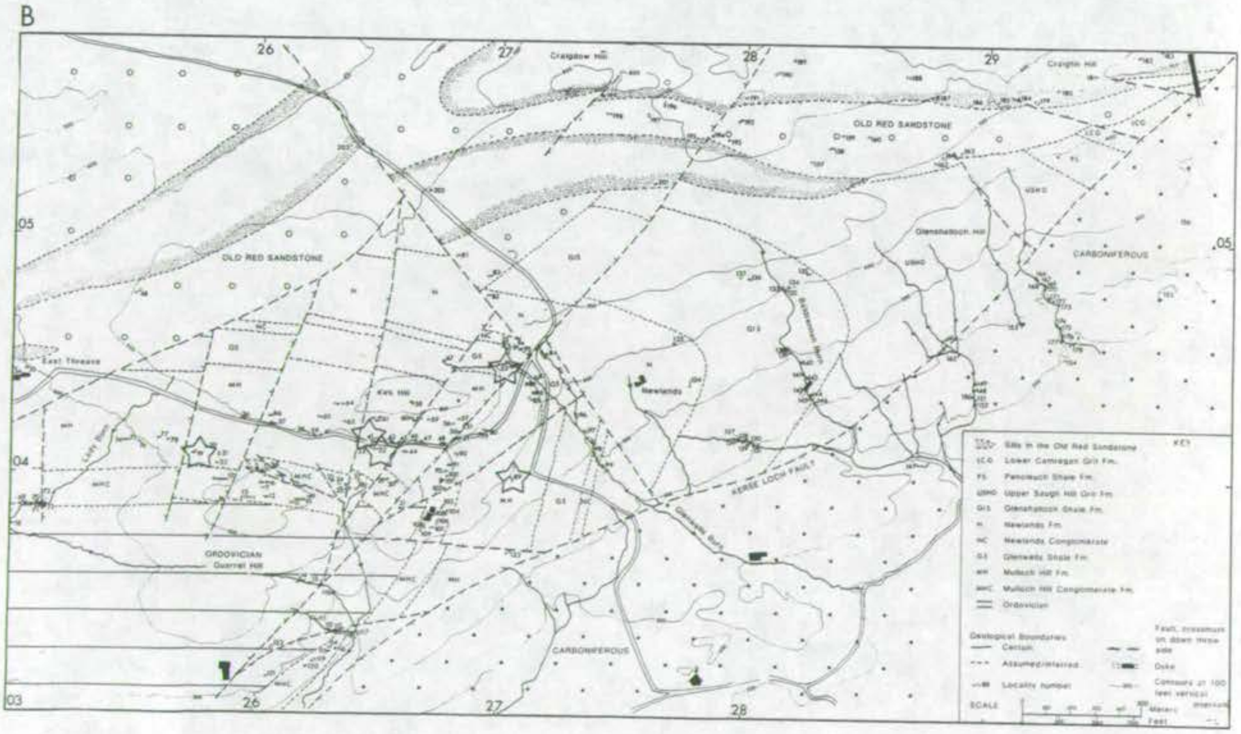
FIGURE 8.1

A

	M.H.C.Fm.	M.H.Fm. Loc.19	M.H.Fm. Loc.32	M.H.Fm. Loc.41	M.H.Fm. Loc.89	G.S.Fm. Loc.53
Lingula sp.	—					
Dalmanellid	—					
Rhynchonellid	—					
Leptaena sp.	—					
Mendacella mullockensis (Davidson)	—	—	—	—	—	—
Zygospiraella scotica (Salter)	—	—	—	—	—	—
Fardenia columbana (Reed)	—	—	—	—	—	
Hyattidina angustifrons (Salter)	—	—	—	—	—	
Rhynchotreta cuneata (Dalman)		—	—	—	—	
Rostricellula mullochensis (Reed)		—	—		—	
Eostropheodonta mullochensis (Reed)		—	—			
Dictyonella sp.			—			
Pectrocrania mullochensis (Reed)					—	
Schizonema subplicatum (Reed)					—	
Stricklandia lens mullochensis (Reed)					—	
Clorinda undata (J. de C. Sowerby)						—
Leangella scissa (Davidson)						—
Eoplectodonta duplicata (J. de C. Sowerby)						—
Eospirigerina cf. gaspeenis (Cooper)						—
Meifoida sp.						—
Whitfieldella sp.						—

Fig(8.1) The stratigraphical distribution of selected brachiopods within the Mulloch Hill Conglomerate Fm. (M.H.C.Fm.),the Mulloch Hill Fm. (M.H.Fm.) and the Glenwells Shale Fm. (G.S.Fm.). Locality numbers refer to fig B.

B



cystoids and graptolites which disappeared at the Rawtheyan-Hirnantian boundary, the brachiopods and corals of the Oslo region suffered the most heavy losses during the early part of the Hirnantian (Baarli & Harper, 1986), and this continued through the Ordovician-Silurian junction (Brenchley, 1984). As in the Girvan district these faunal extinctions have been related to the late Ordovician glaciation.

Much discussion has surrounded the cause or causes of the extinction (e.g. Johnson, 1984; Stanley, 1984). A major cooling event (Stanley 1984 a,b); a restriction of the area of the continental shelves by drainage (Sheehan, 1973, 1977; Jaanusson, 1979; Brenchley, 1984); or major tectonic events (Campsie et al, 1984) have all been argued as causes for the late Ordovician extinctions. Most recently Rong jia-yu and Harper (1988) suggest that the extinction of the *Hirnantia* fauna occurred in response to changes in sea level.

A further cause is invoked by Baarli & Harper (1986) namely competition between relict Ordovician and immigrant Silurian brachiopod stocks. They show that in the Oslo Region brachiopod extinction continued into the earliest Silurian, and consequently a diverse association was already established during the early Llandovery transgression and was only later replaced, after the peak of the transgression, by a typical early Llandovery assemblage of low diversity fauna. They suggest that the lowest Llandovery fauna was dominated by Ordovician forms whose gradual extinction was probably the result of the unsuccessful competition with immigrant Silurian stocks during the initial Llandovery transgression. The more eurytopic Ordovician species had the capacity to create and participate in the new community structure, but as the transgression proceeded more offshore elements may have immigrated, infiltrating this fauna. These originated around the unstable continental margins where both isolation and speciation may have taken place during the late Ordovician regression (e.g. Eldredge, 1974; Fortey, 1984; Neuman, 1984; Bruton & Harper, 1985). As a result of competition with the immigrant species, the relict Ordovician elements were gradually displaced. Eventually a less diverse recurrent assemblage evolved comprising of a mixture of more eurytopic native species and successful immigrants.

Plates 8.1 - 8.10 (Chapter 8)

Plate 8.1

MULLOCH HILL FORMATION

Figure 1 *Petrocrania mullochensis* (Reed, 1917)

1. Internal mould of brachial valve, TW.89.93 x 3.5

Figure 2 *Schizonema subplicatum* (Reed, 1917)

2. Internal mould of pedicle valve, TW.78.94 x

Figure 3 *Mendacella mullockiensis* (Davidson, 1869)

3. Internal moulds of pedicle and brachial valves, TW.89.95 x 3

Figures 4-5 *?Dictyonella* sp.

4. Latex replica of exterior of pedicle valve TW.44.96 x 2.5
5. Enlargement of latex replica of exterior of pedicle valve, TW.44.96 x 2.5

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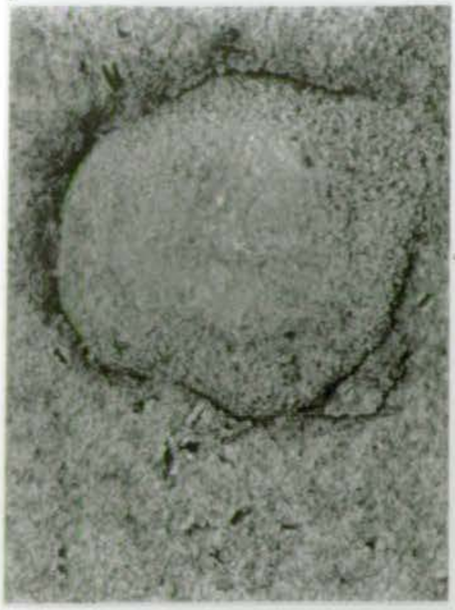

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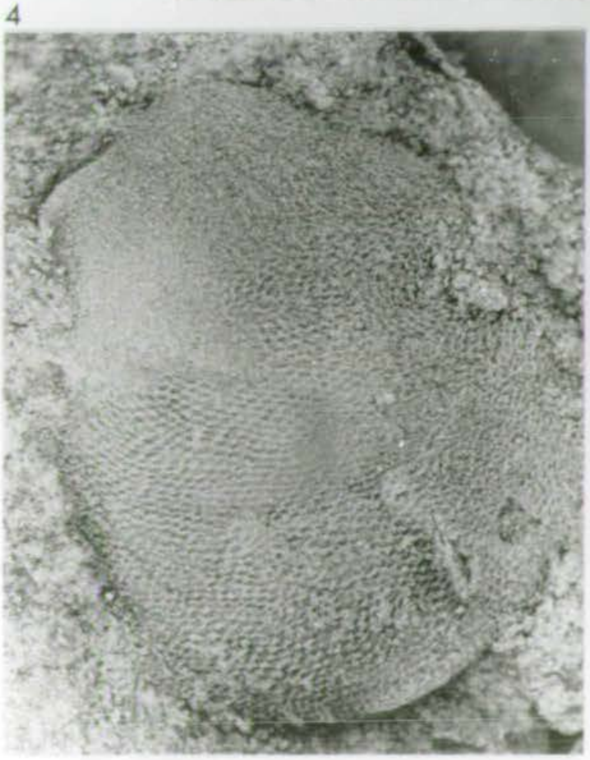

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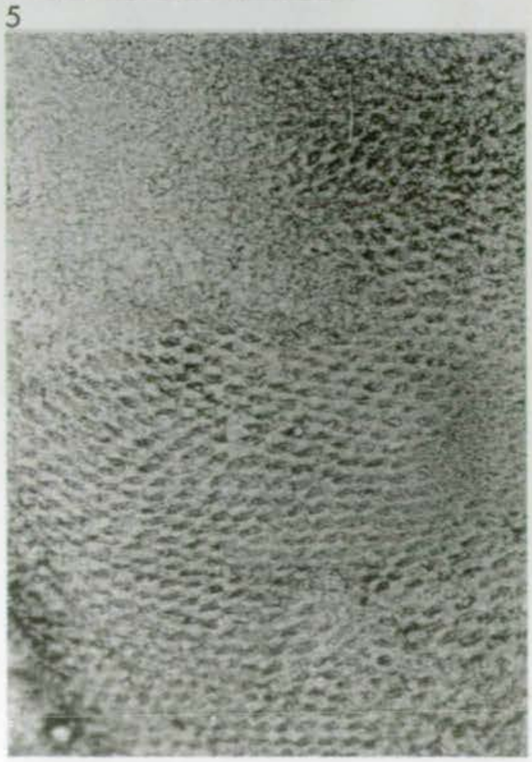

Plate 8.2

MULLOCH HILL FORMATION

Figures 1-9 *Mendacella mullockiensis* (Davidson, 1869)

1.	Internal mould of brachial valve,	TW.89. 79 x 3
2.	Internal mould of brachial valve,	TW.32. 98 x 3
3.	Internal mould of brachial valve,	TW.89. 99 x 3
4.	Internal mould of brachial valve,	TW.89.100 x 4
5.	Internal mould of pedicle valve,	TW.89.101 x 3
6.	Internal mould of pedicle valve,	TW.89.102 x 4
7.	Internal mould of pedicle valve,	TW.74.103 x 3
8.	Latex replica of internal mould, brachial valve,	TW.89. 97 x 3
9.	Latex replica of internal mould, pedicle valve,	TW.89.104 x 3

PLATE 8.2

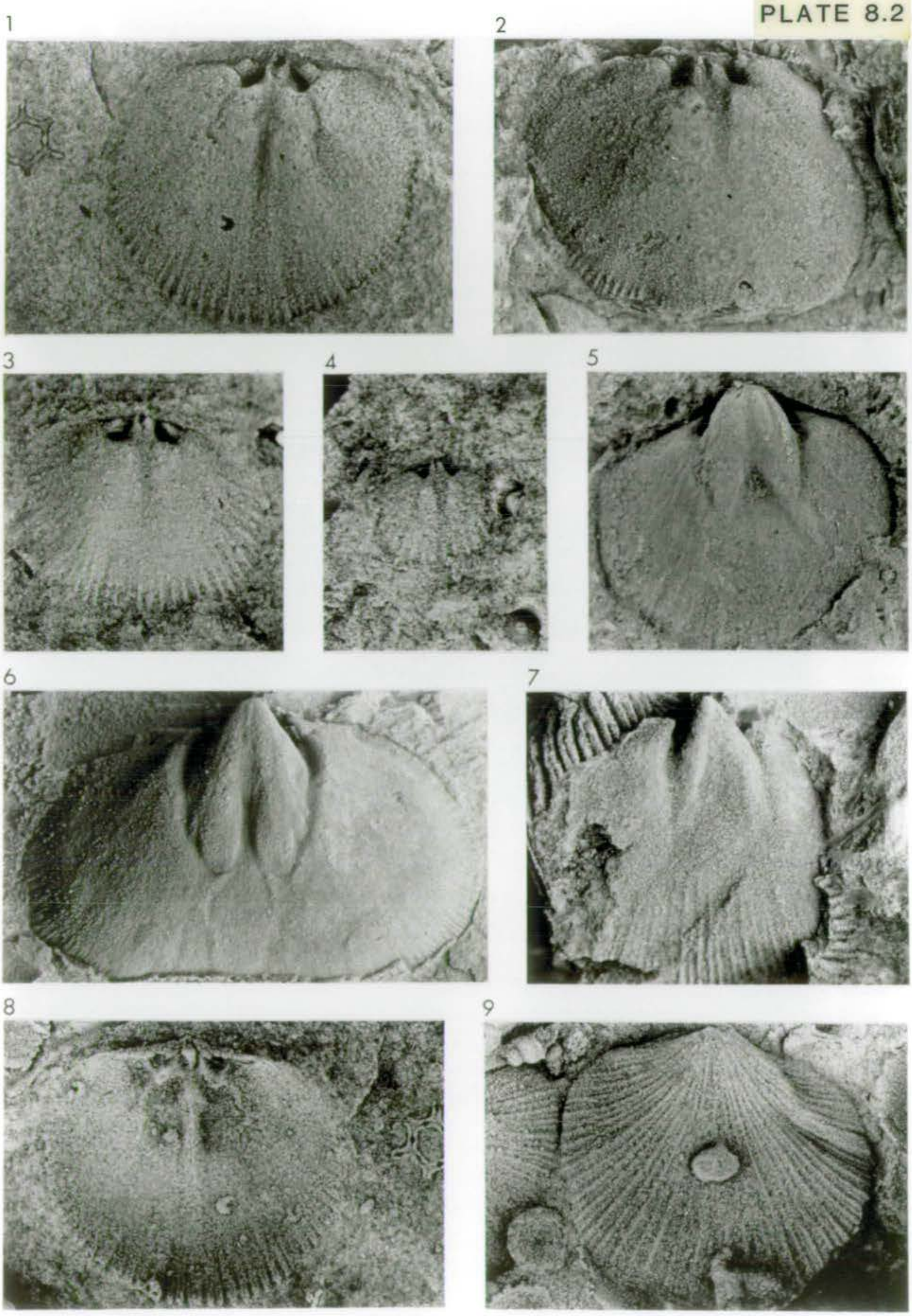

Plate 8.3

MULLOCH HILL FORMATION

Figures 1-7 *Mendacella mullockiensis* (Davidson, 1869)

1. Internal mould of brachial valve, TW.32.105 x 3
2. Internal mould of pedicle valve, TW.32.106 x 3
3. Internal mould of brachial valve, TW.32.107 x 3
4. Latex replica of interior of brachial valve, TW.89.108 x 2
5. Latex replica of interior of brachial valve, TW.89.109 x 3
6. Internal mould of pedicle valve, TW.32.110 x 4
7. Latex replica of exterior, pedicle valve, TW.89.111 x 3.5

Figure 8 *Dalmanellid* sp.

8. Latex replica of conjoined valves, TW.89.112 x 4

PLATE 8.3

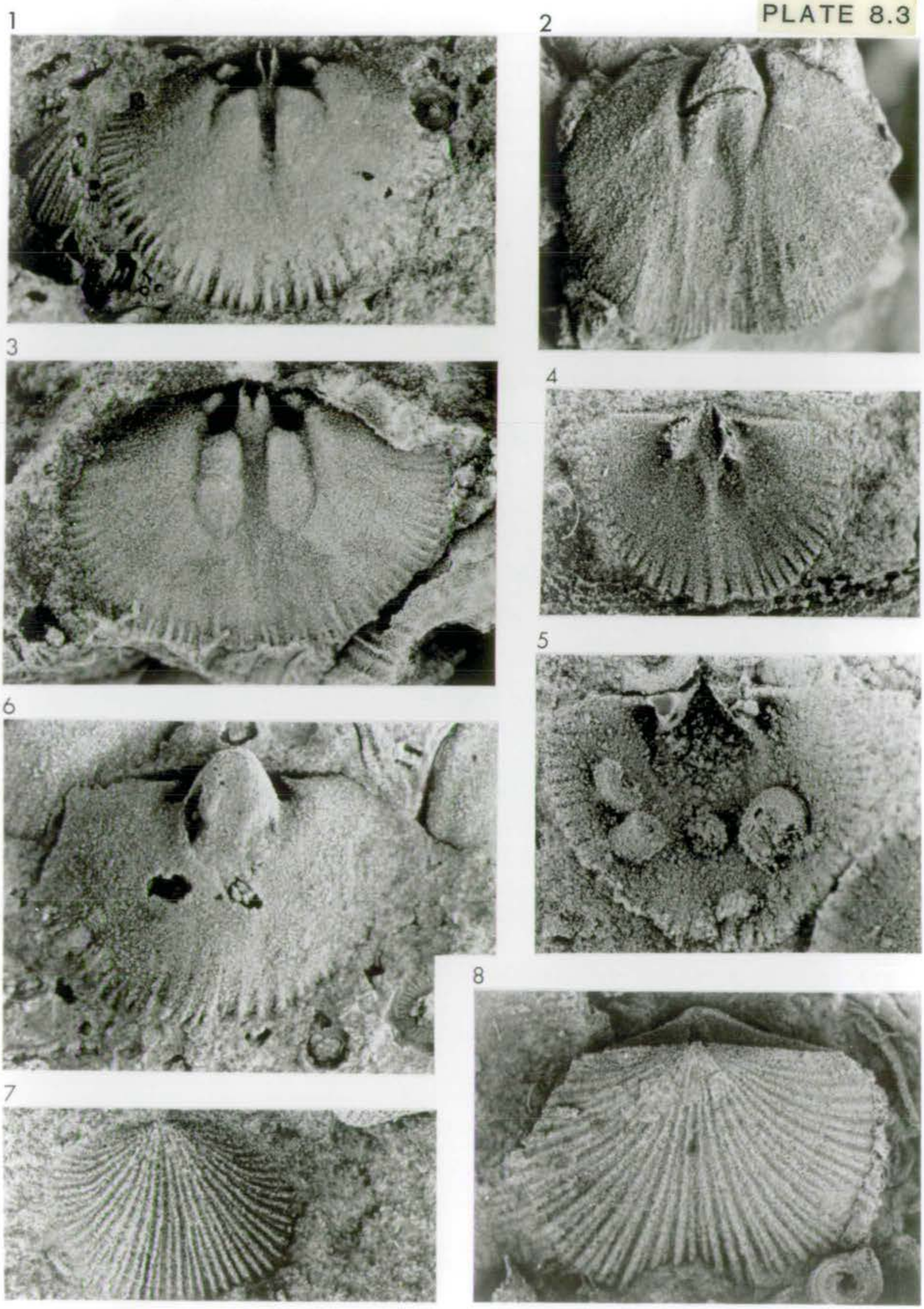

Plate 8.4

MULLOCH HILL FORMATION

Figures 1-3 *Eostropheodonta mullochensis* (Reed, 1917)

1. Internal mould of pedicle valve, TW.89.113 x 2.5

2. Internal mould of brachial valve, TW.89.114 x 3

3. Latex replica of interior of brachial valve, TW.89.114 x 2.5

PLATE 8.4

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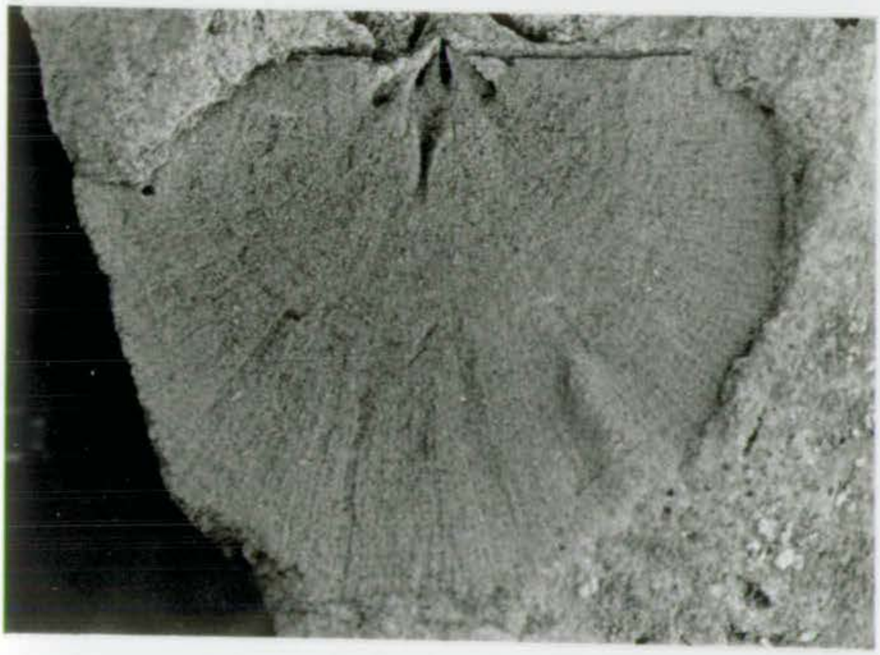

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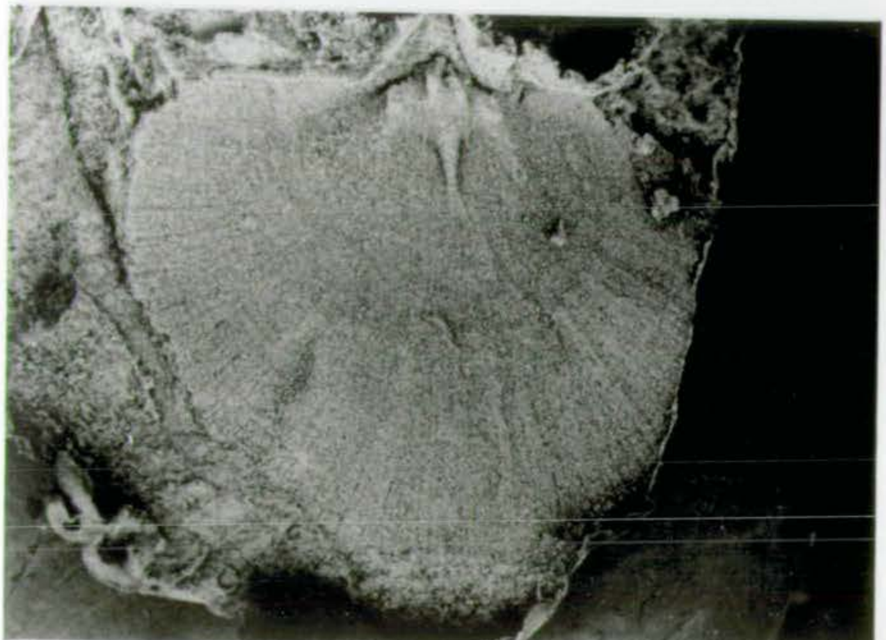

Plate 8.5

MULLOCH HILL FORMATION

Figures 1-5 *Fardenia (Fardenia) columbana* (Reed, 1917)

1. Internal mould of brachial valve, TW.32.115 x 2.5
2. Latex replica of interior of brachial valve, TW.32.115 x 2.5
3. Latex replica of interior of brachial valve, TW.32.115 x 6
4. Latex replica of interior of brachial valve, TW.19.116 x 2.5
5. Latex replica of interior of pedicle valve, TW.89.117 x 2.5
6. Latex replica of exterior of pedicle valve, TW.89.118 x 2.5

PLATE 8.5

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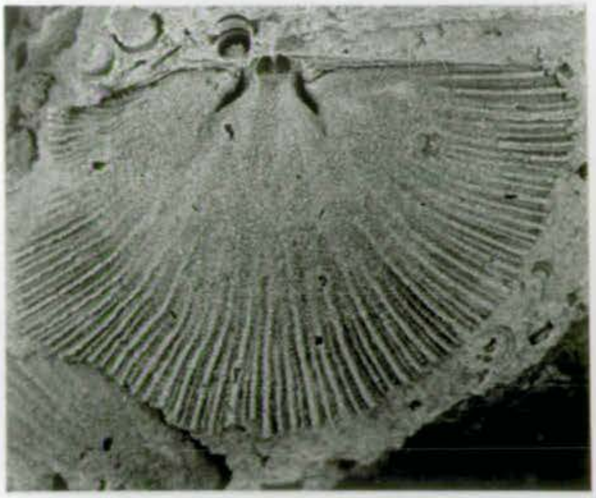

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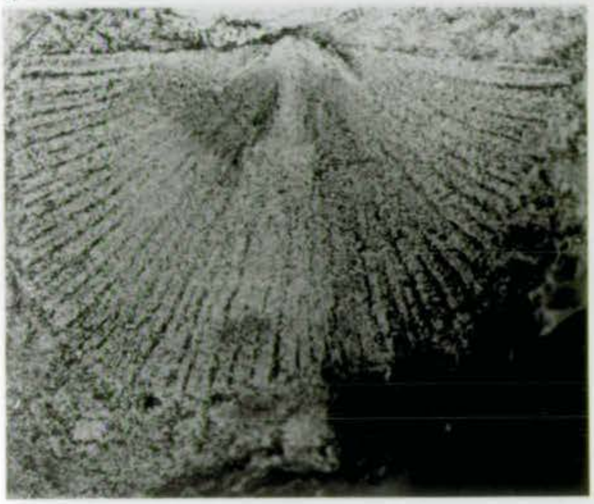

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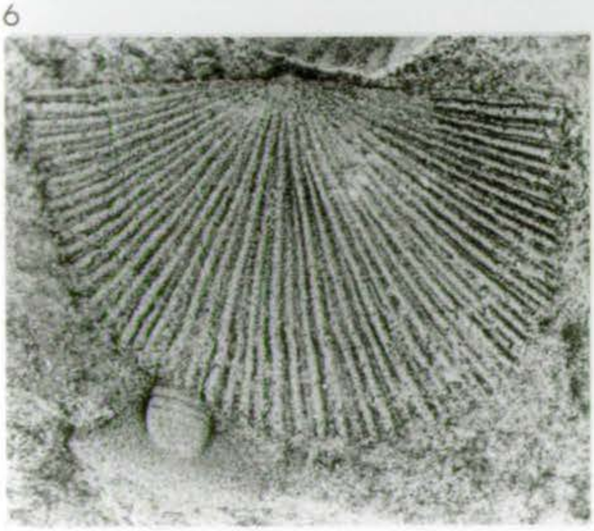

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Plate 8.6

MULLOCH HILL FORMATION

Figures 1-6 *Stricklandia lens mullochensis* (Reed, 1917)

1. Internal mould of pedicle valves, TW.115.119 x 3
2. Internal mould of pedicle valves, TW.115.119 x 8
3. Internal mould of pedicle valves, TW.115.119 x 3
4. Internal mould of pedicle valves, TW.115.119 x 8
5. Internal mould of pedicle valves, TW.115.119 x 8
6. Internal mould of brachial valves, TW.115.119 x 8

PLATE 8.6

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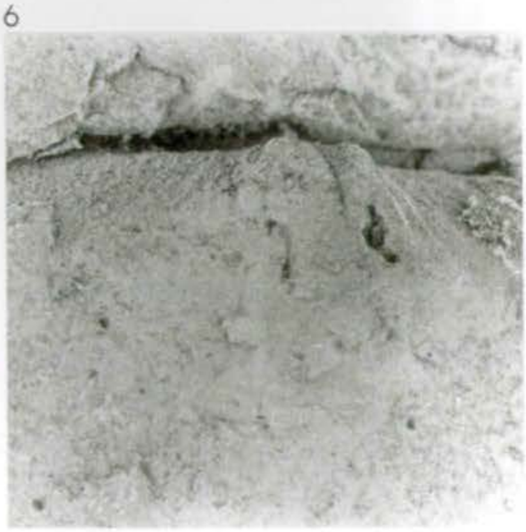


Plate 8.7

MULLOCH HILL FORMATION

Figure 1 ?*Rhynchotreta cuneata* (Dalman, 1828)

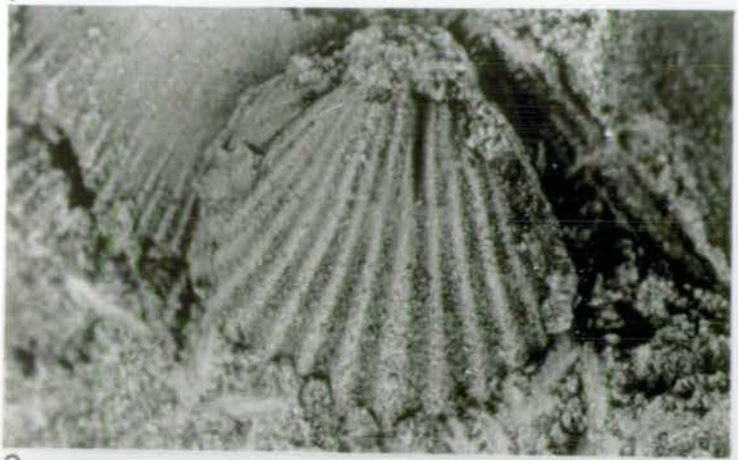
1. Internal mould of brachial valve, TW.89.113 x 3.5

Figures 2-8 *Rostricellula mullochensis* (Reed, 1917)

2. Internal mould of small pedicle valve, TW. .114 x 2
3. Internal mould of conjoined shell, brachial valve, TW. .115 x 3
4. Internal mould of conjoined shell, brachial valve, TW. .116 x 2
5. Internal mould of conjoined shell, brachial valve, TW. .117 x 4
6. Internal mould of conjoined shell, pedicle valve, TW. .118 x 4
7. Internal mould of brachial valve, TW. .119 x 3
8. Internal mould of pedicle valve, TW. .120 x 3

PLATE 8.7

1



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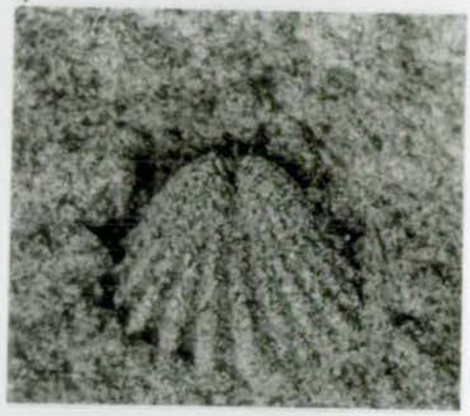

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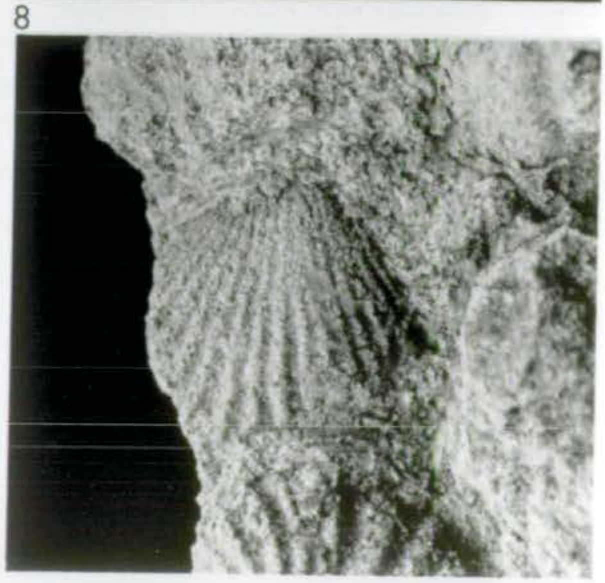


Plate 8.8

MULLOCH HILL FORMATION

Figures 1-6 *Hyattidina? angustifrons* (Salter, 1851)

1. Internal mould of conjoined valves, brachial valve, TW.32.121 x 5
2. Internal mould of conjoined valves, brachial valve, TW.32.122 x 5
3. Internal mould of conjoined valves, brachial valve, TW.32.123 x 5
4. Internal mould of conjoined valves, brachial valve, TW.32.124 x 5
5. Internal mould of conjoined valves, pedicle valve, TW.89.125 x 5
6. Pedicle and brachial valves of conjoined specimen, lateral view, TW.89.122 x 5

PLATE 8.8

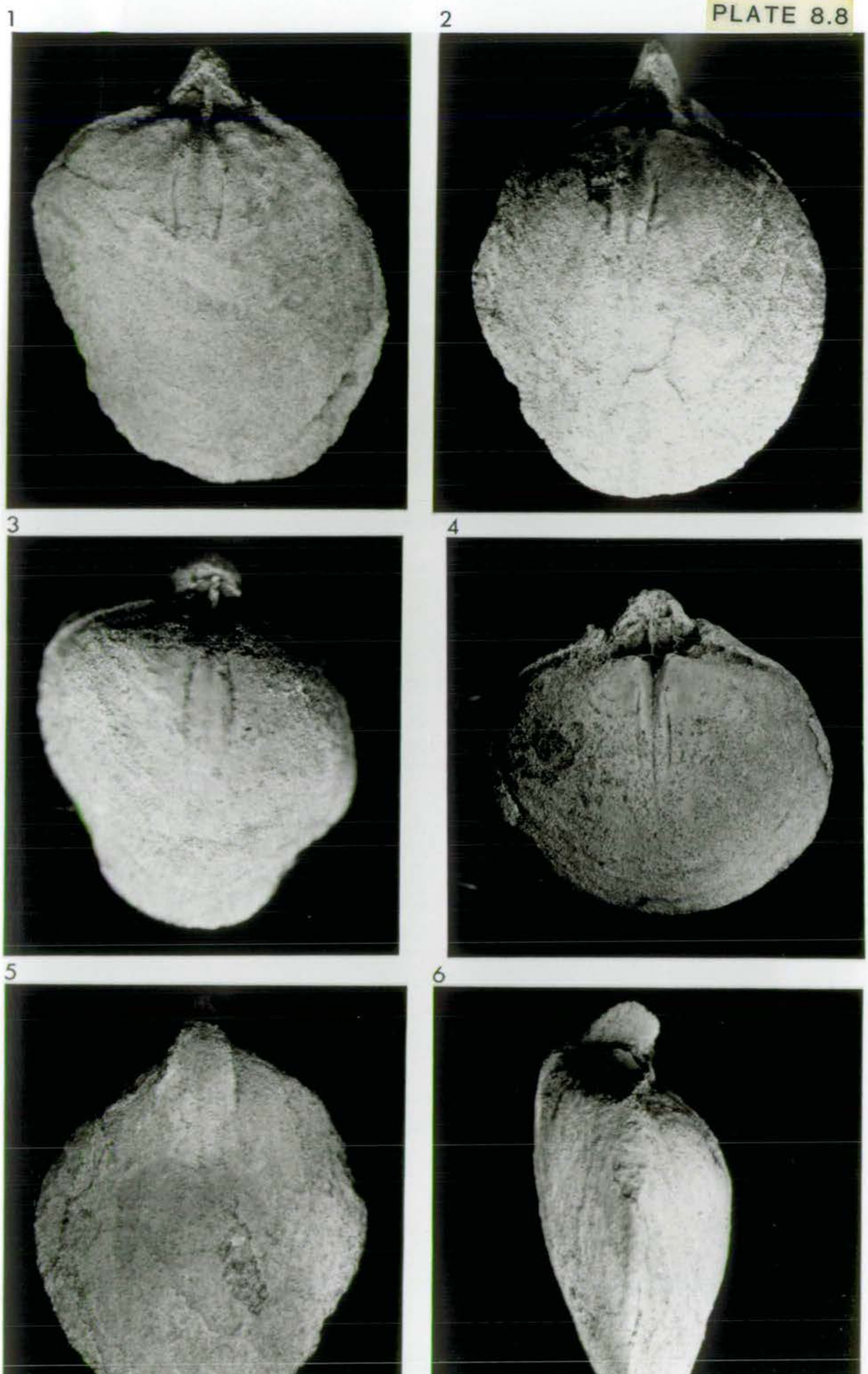


Plate 8.9

MULLOCH HILL FORMATION

Figures 1-6 *Hyattidina? angustifrons* (Salter, 1851)

1. Internal moulds of conjoined valves, TW.89.126 & 127 x 3.5

2. Internal moulds of brachial valves, TW.89.128 & 129 x 4

3. Internal moulds of conjoined valves, brachial view showing posteriorly pitted areas, TW.89.130 x 4

4. Internal moulds of conjoined valves, brachial view showing posteriorly pitted areas, TW.32.131 x 4.5

5. Internal moulds of conjoined valves, TW.89.132 & 133 x 4

6. Internal moulds of conjoined valves, TW.32.134 x 3

PLATE 8.9

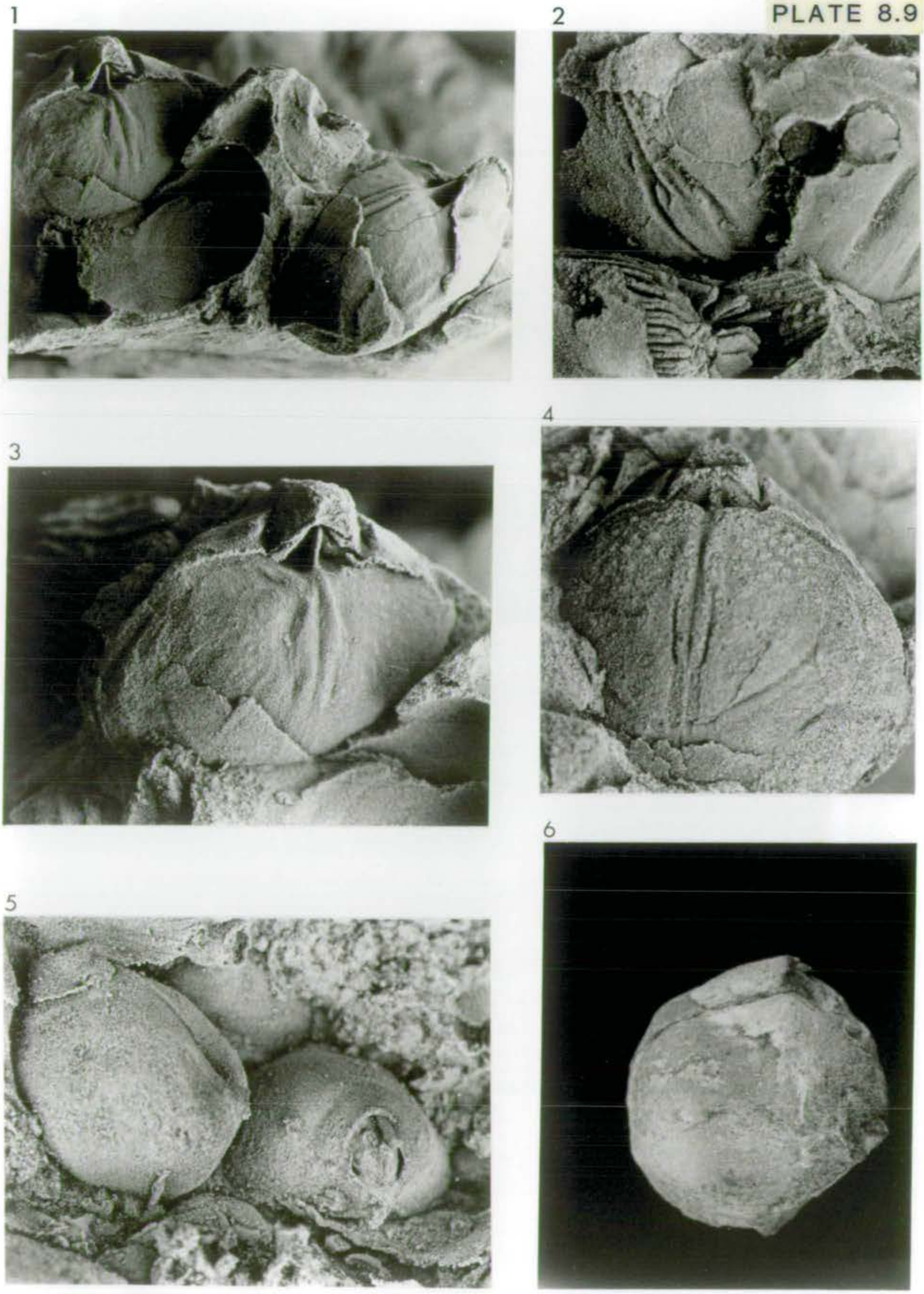


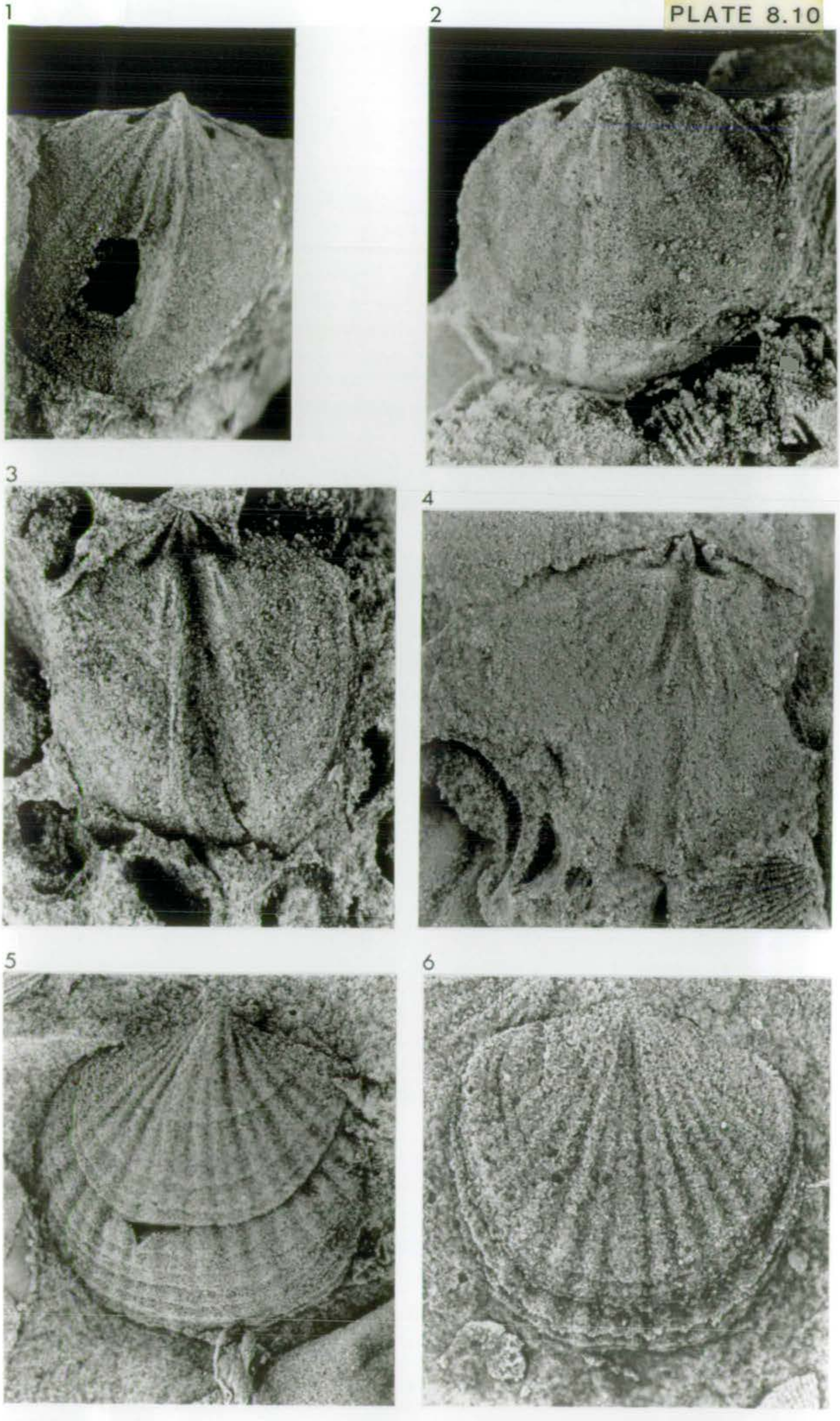
Plate 8.10

MULLOCH HILL FORMATION

Figures 1-6 *Zygospiraella scotica* (Salter, 1851)

1. Internal mould of pedicle valve, TW.89.135 x 4
2. Internal mould of pedicle valve, TW.32.136 x 4
3. Internal mould of brachial valve, TW.74.137 x 4
4. Internal mould of brachial valve, TW.74.138 x 4
5. Latex replica of exterior of pedicle valve, TW.89.139 x 5
6. Latex replica of exterior of brachial valve, TW.89.140 x 5

PLATE 8.10



CHAPTER 9

9. THE PALAEOBIOLOGY AND PALAEOECOLOGY OF THE MULLOCH HILL GROUP (CRAIGHEAD)

9.1 INTRODUCTION

Palaeoecology is the study of ancient organisms in relation to their environment. It is based upon the uniformitarian assumption that the present is the key to the past and that the life modes of ancient organisms, especially of extant analogues of the same species, can be inferred. Unfortunately there are no direct modern day analogues to compare with Silurian species, which brings to light one of the limitations impairing palaeoecological studies. This can be at least partially overcome by examining modern counterparts belonging to similar morphological or taxonomic groups. Some further insight as to the nature of the environment inhabited can be derived from functional interpretation of fossil structures, in terms of their original mode of life.

The environmental distribution of fossils depends on a number of factors, whose importance in particular instances is debatable: 1) substrate conditions, 2) space, 3) temperature, 4) pressure, 5) light, 6) water movement, 7) water chemistry, 8) nutrients, 9) dissolved gas, 10) biological interactions (Savilov, 1957; Walker and Bambach, 1974) and these are reviewed by Moore (1958) and Boucot (1981).

Providing that its strengths and limitations are fully understood, the study of palaeoecology is still a very valuable science, contributing to a greater knowledge of the depositional setting which the fossils studied inhabited.

9.2 DISCUSSION OF THE FOSSIL ORGANISMS

The Mulloch Hill Group, consisting of the Mulloch Hill Conglomerate, Mulloch Hill Formation and Glenwells Shale, was chosen for this study because of: 1) the relatively large number of good exposures, 2) the abundance and the diversity of fossils and 3) because the Group immediately overlies the Ordovician-Silurian boundary. Although some of the fossils may have been locally transported, palaeoecological studies still provide information about the habitat in which the organisms originally lived. The fossils have already been identified in Section 7, and in this chapter (of the most commonly occurring fossil taxa) possible modes of life, by comparison with living counterparts, are discussed systematically; and with particular reference to the recent compilation in autecology of Silurian organisms edited by Bassett and Lawson (1984). The terminology employed for organism-substrate relationships closely follows that recommended by West (1977) with the main exception that the terms hard bottom and soft bottom are used, rather than solid and loose substrate.

9.2.1 Plants

For a long time the affinities of *Cyclocrinites favus* (Nitecki) from the Mulloch Hill Group, provoked much discussion, suggestions being as diverse as sponges, bryozoans, corals, and gastropod eggs, to name but a few. It was first recognised as a calcareous dasycladaceae alga by Stolley in 1896, who examined Ordovician specimens from the Baltic region. Originally the thallus of the cyclocrinitid was ovoid to spherical and enclosed a hollow space with a central axis. Radiating outwards from the stem the lateral branches possessed thick hexagonally shaped heads at the top, which were tightly packed together, so as to give the appearance of a honeycomb. Individual thalli were attached to the substrate by the central axis, and when they grew to a large size, before death they were susceptible to collapsing under their weight (Beadle & Johnson, 1986).

The distribution of cyclocrinitids was influenced by light intensity and current strength. Since their thalli were weakly calcified and hollow it is presumed that they were fairly fragile and thus preferred sheltered, low energy environments (Beadle & Johnson, 1986). By attaching themselves to solid objects such as shells, they were able to live on otherwise soft substrates, but they were unable to cope with movements or resuspension of the substrate. By analogy with recent dasyclads, it is virtually certain that cyclocrinitids probably lived at depths of less than 100 metres, but a correlation of size with relative depth has been suggested; advocating that cyclocrinitids with small adult thalli lived in deep dark waters whereas cyclocrinitids with larger thalli lived in shallow water (Beadle & Johnson, 1986).

In the Craighead Inlier, the cyclocrinitids are only found in the upper part of the Mulloch Hill Formation, viz. the Glenwells Shale and Newlands Formation, associated with typical Palaeozoic marine faunas. Presumably these cyclocrinitids lived below the normal water base, no deeper than 100m, thus restricting them to well oxygenated waters where the light intensity was relatively high and the water energy was low. This is also confirmed by the sedimentological evidence.

9.2.2 Corals

Modern corals are solitary or colonial marine suspension feeders, which may be divided into two ecological groups, 1) hermatypic corals, which are dependant on symbiotic algae (zooxanthellae) and consequently are restricted to warm, shallow marine waters, in the photic zone, 2) ahermatypic corals, which are not restricted to any environment and therefore can live in deeper waters. Tolerance of turbulent conditions, agitated waters and high sedimentation rates, is low for most modern corals.

The corals in the Craighead and Girvan shore sequence are represented by two orders: Rugosa and Tabulata. These corals, and other Palaeozoic corals are thought to have lived a hermatypic mode of life, restricted to warm shallow marine waters in the photic zone. The shape and size of the corallum of the solitary rugose coral *Rhagmophyllum crenulatus* (McCoy) was possibly influenced by the rate of sedimentation, and it was probably attached to the sea floor whereas the tabulate corals *Favosites* and *Halysites* are compound, and lived freely on the substrate surface (Wells, 1957). Hard substrates provided additional stability, when the corals grew over and around them (Brett & Cottrell, 1982).

9.2.3 Bryozoans

Bryozoans are sessile, colonial, mainly marine filter feeders. The colony is an integrated operational unit (Cowen and Rider, 1972) where individual zooids interact to form a single complete organism and thus maximise the competence of the filtering system. Because they are dependent upon environmental conditions (Boardman et al. 1983; Bretsky, 1970; Lagaaij & Gautier, 1965) turbulence, sedimentation rates, and the availability of hard substrates upon which they may settle, are important factors influencing their distribution.

Bryozoans present in the Mulloch Group are mainly erect articulated species of *Ptilodictya*, which are very delicate and appear to have been prone to skeletal damage, indicating that in the environment that they originally inhabited the rates of sedimentation could not have been high. Nor could they have withstood significant transportation as they would have fallen to pieces. They are exclusively marine, and are found in relatively shallow environments. It would be expected that the forms with articulated stems should be characteristic of agitated waters with heavy current and wave action, but except for *Ptilodictya flabellatiformis* (Kopaevich), most articulated species show the same distribution as the erect form. Recently erect growth has been viewed as a type of fugitive strategy for escaping from spatial competition on the substratum (Taylor, 1984).

Silurian bryozoans were active suspension feeders that feed on small phytoplankton (Winston, 1981) feeding by filtering water through a lophophore.

9.2.4 Brachiopods

Brachiopods are benthic marine filter feeders and are divided into two classes: Inarticulata and Articulata. Living inarticulates such as the infaunal lingulids are tolerant of a variety of environments, ranging from brackish nearshore water to normal marine offshore waters. Their distribution however, is critically related to sediment consistency and rate of sedimentation. Articulate brachipods, however, cannot generally tolerate brackish conditions, since they are stenohaline (Rudwick, 1962, 1970).

Generally the distribution of modern brachiopods is controlled by the limited distance that larvae may travel, by the availability of attachment sites, and to a lesser extent by subtle environmental differences. As a result, the brachiopods tend to grow in clusters (Hallam, 1962). Most brachiopods cannot withstand active sedimentation, but there are some which are tolerant of turbid conditions (Rudwick, 1962).

Living brachiopods feed by indiscriminately extracting suspended particles of food from the seawater or possibly colloidal material; the cilia create inhalent currents which bring the food particles to the mouth and the waste products are disposed by means of the exhalent currents. Some of the living brachiopods (in quiet water conditions) have a median deflection or indentation in the anterior margin of the shell which separates the medial exhalent currents from the lateral inhalent currents, whereas in slightly more agitated water conditions some shells may develop a zig-zag commissure, which prevents large, harmful sand grains entering the shell, whilst simultaneously increasing the effective length of the commissure through which food-bearing currents can be taken in.

On the bases of life habit types, the brachiopod present in the Mulloch Hill Group can be divided into four groups (Surlyk, 1972; Bassett, 1984) (Fig. 9.1)

1) Brachiopods which attached to the substrate by means of a pedicle.
2) Brachiopods which lived free on the substrate.
3) Brachiopods which burrowed into the substrate.
4) Brachiopods which cemented themselves to the substrate.

<u>Group 1: Pedunculate Brachiopods</u>

In the early stages of development, most brachiopods have some form of pedicle and depending on the species, the pedicle may exist for the full duration of life or may gradually disappear. Usually the pedicle attaches itself by mucal adhesion of the distal tip to hard substrates, for example rocks, pebbles and shells - only rarely are living brachiopods attached directly into soft sediment. Normally pedicles are not preserved in the fossil record because the organic tissue decomposes rapidly after death. The pedicle varies considerably in length, and thickness and may expand or contract outside the shell, therefore foramen size is not necessarily a reliable guide to functional diameter or strength. It may be inferred that fossil brachiopods were pedunculate if they were devoid of delthyrial covers, or if these were only poorly developed as in most orthids, rhynchonellids and spiriferids.

None of the brachiopods found in the Craighead Inlier or the Girvan shore was found to be attached to a hard substratum nor in any instances was the pedicle stalk retained. Most of the brachiopods in the Mulloch Hill Group such as *Hyattidina*, *Mendacella* and *Rostricellula* have an open delthyrium and hence must have had a

Fig. 9.1 Life-habit groups of the brachiopods from the Mulloch Hill Group.

Symbols: • primary life-habit, ? possible life-habit.

Formation	Brachiopod fauna	Pedunculate	Life Habit Free Living & loosely attached	Burrowing
Mulloch Hill Conglomerate Fm.	*Lingula* sp.			•
	dalmanellid sp.	•		
	rhynchonellid sp.	•		
	Fardenia sp.		?	
	Leptaena sp.		•	?
Mulloch Hill Fm.	*Hyattidina angustifrons*		•	
	Zygospiraella scotica	•		
	Mendacella mullockiensis	•		
	Schizonema subplicatum	•		
	Isorthis amplificata	•		
	Resserella canalis	•		
	Rhynchotreta cuneata	•		
	Rostricellula mullochensis	•		
	Fardenia (Fardenia) columbana		?	
	Eostropheodonta mullochensis		•	
	Pectrocrania mullochensis		•	
	Stricklandia lens mullochensis		•	
	Dictyonella sp.		?	
Glenwells Shale Fm.	*Skenidoides*	?		
	Clorinda undata.	?		
	Leangella scissa		•	
	Eoplectodonta duplicata		•	
	Leptaena sp.		•	
	Eospirigerina sp.	?		
	Meifoidia sp.		?	
	Whitfielda sp.	•		

functional pedicle, though whether or not this was attached to a substratum remains unknown. Only a few of these brachiopods, such as *Hyattidina*, *Mendacella* and *Clorinda* possess very shallow median deflections, and rarer still are shells with zig-zag commissures, such as *Rostricellula* (Fig. 9.1).

Group 2: Free-living Brachiopods

Unlike modern brachiopods, many of the fossil groups (viz. most strophomenides and some spiriferides), possess covered or plugged pedicle openings which could not have borne a strong functional pedicle or if it existed as a thin strand they were so loosely tethered by it that they lived unattached on the substrate surface. At early growth stages, the brachiopods are termed ambitopic (Jaanusson et al. 1979). Some free living chonetid brachiopods may have been capable of swimming short distances by vigorously opening and closing their valves (Bergström, 1968). *Leptostrophia* and *Eostropheodonta* (the latter, present in the Mulloch Hill Formation) possess the same general features, being both thin shelled, with weak curvature. It appears that at a very early growth stage the pedicle opening was sealed and secreted a mucus-like substance on the topmost surface of the sediment. *Cryptothyrella*, as known from the Lower Llandovery of Ohio and Kentucky (Gauri and Boucot, 1970), also probably closed the pedicle opening and adopted a free living strategy.

A wide range of morphological stabilising mechanisms prevented disturbance by turbulent currents or partial or complete burial. Some of these mechanisms are evident in the brachiopods of the Mulloch Hill Group. For example during ontogeny, the shells of *Eoplectodonta*, from the Glenwells Shale, became more concavo-convex, a device which would increase stability in strong currents. It is assumed that these species rested on or just in the sediment on their convex pedicle valve. The saucer or dish shaped convexity of the upper valve allowed the commissures and growing mantle edges to be held above the substrate, and if the shell sank too far, it is probable that the shell would have been lifted back upwards by means of vigorous snapping of the valves (Rudwick, 1970).

Leangella, also from the Glenwells Shale, shares the same general features as *Eoplectodonta*, and it is presumed they had a similar strategy, utilising the lateral extension of the cardinal angles as short alae to spread the weight of the shell across a greater area of sediment, thus improving further the stability and support. By contrast with species, *Leptaena* could have lived entirely within the sediment with the vertical commissure above the surface, without needing periodically to snap the valves, to reach the surface (Bassett, 1984).

Other stabilising mechanisms, which are not evident in the faunas discussed here, include increase in shell weight at the posterior of the shell, increase in size of interarea, development of spines and the development of frilly shell extensions.

Group 3: Burrowing Brachiopods

Among recent brachiopods, lingulids are the only fully infaunal group. At low tide, or for protection, the lingulids will withdraw into their burrows, and move up to the surface for feeding. Permanent enclosure within the sediment is not possible.

Lingulids possess a close set of siphon-like erectile structures at their mantle edges, and can consequently form deep vertical burrows (Rudwick, 1970).

In Craighead *Lingula* sp. were found in the Mulloch Hill Conglomerate (Craighead) and in the Woodland Formation (Girvan Shore), and it is assumed to have followed a burrowing mode of life.

Group 4: Encrusting Brachiopods

There are a few cases in recent brachiopods, where the brachiopods are cemented to a substrate. On or almost immediately following larval settlement, cementing brachiopods attach themselves ventrally to a hard bottom (Rowell, 1960; Rudwick, 1970). An example of a recent cementing brachiopod is the calcareous inarticulate *Crania*, whose ventral mantle edge remains in contact with the substrate entirely or almost entirely throughout ontogeny, secreting a shell that follows the topography of the attachment surface. The cementing medium consists primarily of a film of mucoploysaccharide that sticks the outer membrane of the periostracum to the substrate (Williams & Wright, 1970).

The morphology of the Silurian *Petrocrania*, found in the Mulloch Hill Formation, compares well with that of the Recent *Crania*, and it is presumed that it led a similar mode of life, cemented to a wide range of hosts such as brachiopods, corals, but there is no evidence which might suggest that these cementing shells could extend on to the soft bottoms. *Petrocrania* probably lived both epozoically on its host shells and attached itself to dead skeletal material. Also *Orbiculoidea* may have had a similar moulding habitat.

9.2.5 Gastropods

Gastropods are mobile organisms which can live in marine, freshwater or terrestrial environments. Modern gastropod faunas are dominated by caenogastropods, members of the Orders Mesogastropoda and Neogastropoda, characterised by possessing a monopectinate ctenidium whereas most of the Silurian gastropods are members of the Order Archaeogastropoda (Knight et al. 1960), possessing a bipectinate ctenidium.

The bipectinate ctenidia in recent archaeogastropods cannot cope with fine-grained sediment in suspension (Yonge, 1947) and therefore these gastropods tend to be grazing herbivores limited to firm substrates, contrasting with the algal grazing, infaunal and epifaunal deposit feeding, and scavenging to name but a few habits in living caenogastropods (Peel, 1977). Many Silurian archaeogastropods are preserved in fine-grained sediment, and these may have morphologically adapted to living on soft substrates (Wänberg-Eriksson, 1979). Some of the Silurian archaeogastropods were probably non-herbivores and if this was so such ancient archaeogastropods may have lived in a wider range of ecological niches than their modern counterparts so direct comparisons between ancient and modern archaeogastropods are not simple (Peel, 1977).

According to Peel's classification (1978) the Mulloch Hill Group gastropods may be divided into three life-habit groups:

1) Gastropods which lived on soft substrates.
2) Gastropods which lived on firm substrates.
3) Foliage supported gastropods.

Group 1: Soft-substrate Gastropods

Murchisonia sp. and *Loxonena* sp. are high spired gastropods interpreted as monopectinate caenogastropods (Peel, 1978) which were able to move freely in the soft sediments (Fig. 9.2). Although these gastropods were most likely herbivores, the possibility that they may have been ciliary feeders, scavengers or even carnivores can not be ruled out.

Group 2: Firm-substrate Gastropods

The majority of the gastropods in the Mulloch Hill Group lived on firm substrates and in particular the trochiform pleurotomariaceans; *Loxoplocus* sp., *Phanerotrem* sp. The possession of bipectinate ctenidia in these gastropods is thought to have restricted them to hard substrata and, on the basis of its morphological similarity to the present day *Vermicularia* sp. (Peel, 1975) to have been ciliary deposit feeders.

Fig. 9.2 Life-habit groups of the gastropods from the Mulloch Hill Group. Symbols: • primary life-habit, ? possible life-habit.

Gastropods	Soft	Hard	Foliage
Loxoplocus (Lophospira) sedgwickii		•	
L. (L)		•	
Loxonema sp.	•		
Murchisoniacean sp.	•		
Kohenospira sp.		?	
Phanerotrema sp.		•	
Liospira marklandensis sp.			?
Arjamannia sp.		•	

Group 3: Foliage supported Gastropods

In modern seas, plants such as algae and sea grasses provide micromorphic gastropods with abundant food and refuge both from predators and from strong currents. This may have also been the case in ancient seas. It is possible that the occurrence of bipectinate archaeogastropods in soft sediments may reflect such a mode of life assuming that the organic plant material may have decayed, but this need not have been so.

Only one lenticular pleurotomaricean was found in the Mulloch Hill Group, namely *Liospira* sp.. Since Silurian pleurotomariceans are presumed to indicate near-shore shallow water environments (Boucot, 1975) and similar grazing gastropods are found in near-shore coastal environments, in the subtidal zone (Kinsman & Park, 1976) the *Liospira* presumably also participated in a near-shore grazing mode of life.

Summary of Gastropods:

In the Mulloch Hill Group, trochiform pleurotomariaceans interpreted as deposit feeders are dominant (63%) and are associated with a hard substratum. These lived in a shallow marine platform environment, in clear water, and it is notable that while trochiform pleurotomariaceans are very common, trochiform holopeids are absent. Only 37% of the gastropods are the high spired forms which lived freely on the substrate. Lenticular pleurotomariaceans form a negligible proportion of the gastropod (2%) and probably may have grazed amongst the *Cyclocrines favus* (Nitecki) algae.

Vermeij (1971) argued that the absence of high spired shells amongst recent archaeogastropods is probably because archaegastropods of such a form would accumulate fine suspended sediment and fatally becoming clogged up. A more stable shell form is required for the relatively high energy conditions commonly associated with hard substrata.

9.2.6 Cephalopods

Cephalopods are vagile marine molluscs. Modern cephalopods can swim through the water column relatively rapidly by jet propulsion.

The cephalopods can be sub-divided into two groups: 1) ectocochlear forms, in which the shell is wholly external to the body, and 2) endocochlear forms, in which the shell is wholly internal to the body. It is assumed by most authorities and confirmed by Stürmer's (1970) x-radiographs that Silurian cephalopods were ectocochlear. The only surviving ectocochlear cephalopod is *Nautilus*, found in deep waters between 300-500m, migrating seasonally shorewards (Mutvei, 1979 and Ward, 1987).

Although *Nautilus* is a benthic scavenger, living endocochlear cephalopods are nearly all carnivores. It is probable that most Silurian cephalopods were either scavengers or carnivores (Marek, 1971) living on larvae, soft bodied animals, and carrion and some cephalopods may possibly have been herbivores.

During this investigation only a couple of small fragments of *Orthoceras* sp. have been recovered from the Rough Neuk Quarry (Mulloch Hill Formation). According to Watkins (1979) *Orthoceras* sp. were probably pelagic cephalopods, which may have been unable to migrate outwith current systems (Hewitt & Watkins, 1980) and possibly drifted with the plankton. Orthocone shells are much commoner generally in very shallow water nearshore deposits and it is not surprising to find few in the Mulloch Hill Formation.

9.2.7 Bivalves

Bivalves are benthic infaunal or epifaunal molluscs. Modern bivalves are abundant and diverse, occupying a wide range of ecological niches, in normal marine, brackish and freshwater conditions. Most modern bivalves are suspension feeders, drawing water with suspended food particles into the shell by ciliary action, and then expelling the waste products. Consequently modern suspension feeders possess inhalent and exhalent siphons (Stanley, 1968). On the other hand there are only a few deposit feeding bivalves which extrude palp proboscides into the sediment and collect organic detritus (Yonge, 1939). In general terms a bivalve's mode of life can be inferred by the shape and general morphology of the shell (Stanley, 1970).

Although bivalves have been collected from the Craighead Inlier (Hind, 1910) only unidentifiable fragments were found during this investigation, of no palaeoecological value.

9.2.8 Trilobites

Trilobites are an extinct group of vagile marine arthopods. What is known about their modes of life is based upon trace fossils, studies of functional morphology and the facies which they occur. Most were benthic crawlers, many were shallow burrowers, others were possibly nektobenthic or pelagic; (Clarkson, 1986; Fortey, 1985).

The majority of trilobites were probably either deposit feeders or filter feeders, although some may have been scavengers or active carnivores. In the case of the deposit feeders, the trilobites may have indiscriminately ingested organic-rich sediment from the sea floor or were more selective when gathering food (Mikulic & Watkins, 1981).

9.2.9 Ostracods

Ostracods are vagile, mostly benthic, marine, brackish and freshwater crustaceans. Recent ostracods predominantly live on the bottom of the sea floor crawling or burrowing - only a few ostracods are free-swimming and floating. Their size, shape, and sculpture generally relates to the stability, grain size and pore size of the substrate

(Brasier, 1980) whilst their distribution is mainly controlled by depth and salinity. Modern ostracods are filter-feeders and scavengers, congregating around marine plants for food and protection.

Ostracods were found in the Glenwells Shale, yet due to poor preservation they were unidentifiable and therefore only broad and general deductions can be made about their presence. Since freshwater and deep sea Silurian forms are unknown, Silurian ostracods were mostly benthic filter feeders and scavengers, inhabiting brackish and shallow marine environments. In the Mulloch Group there is no evidence that brackish water conditions prevailed, and the ostracods in the Glenwells Shale are presumed to have lived in shallow marine conditions.

9.2.10 Pelmatozoans

Crinoids are mainly benthic marine suspension feeders. Modern crinoids are muco-ciliary filtration-fan feeders (Franzén, 1983) which, depending on their height, flexibility, variation in crown, stem and root morphology occupy different niches. Generally they prefer habitats with low sedimentation rates. Rheophilic (current-seeking) crinoids possess long flexible stems and arms, which spread out to form a vertical filtration-fan. Rheophobic (current-avoiding) crinoids, in contrast, have short rigid stems and arms, spreading out to form a horizontal collecting bowl (Fell, 1966; Breimer, 1969; Meyer, 1973). Observations of living crinoids (Macurda & Meyer, 1974, 1976) demonstrate that most species, including even deep-water stalked forms, make use of at least moderate currents for feeding and thus can be considered rheophilic.

Most Silurian crinoids were sessile, passive suspension feeders elevated on stalks above the sediment substrate and permanently anchored by holdfasts. Suspended food, was captured on mucus strands, secreted by feeding tube feet and placed into the food groove, and then the mucus-coated food was transported to the mouth by ciliary action. The crinoids generally display considerable variation in column length, and the different forms may have exploited different levels above the substrate (Lane, 1973; Auisch, 1980a, b).

The only complete crinoid specimens in the Mulloch Hill Group were found in the Rough Neuk Starfish Bed. The stalks of these disparid crinoids are relatively short in proportion to their body, serving to anchor the animal against lateral movement by waves or currents, and to elevate the crown above the sea floor. This ensures that the crown is remote from the near-substrate zone where sediment accumulation is most active, where oxygen levels are lowest and where competition for food is most intense. The stalk is relatively slender and appears to have been fairly flexible.

Although the anchoring mechanism was not preserved in the Craighead specimens disparids were generally permanently attached by means of primary discoidal holdfasts.

The sparsely branched arms of the inadunates are thought to have been capable of gathering fairly large particles, and the small size and fragile crown habit suggests quiet water conditions consistent with the fine grained texture of the sediment, in which these crinoids occur. Diversity is low relative to equivalent occurrences elsewhere, for example the Upper Ordovician Girardeau Limestone (Illinois and Missouri) eighteen species, and the Rochester Shale, Wenlock, Lockport, New York) with thirty five species. The prevailing quiet water conditions may have limited diversity, as most recent crinoids prefer moderate to strong agitation, ensuring a continual supply of dissolved oxygen and planktonic food (Fell, 1966).

Petalocrinus, occurring in the Mulloch Hill Formation, did not form a filtration fan since the arms are fused and rigid. Instead, individuals collected settling particles on passive, rigidly held baffles. Since the fused arm fans would have been disadvantageous in strong currents, causing drag, these appendages would have functioned optimally in very low energy environments (Frest & Strimple, 1977). Therefore the rigid and broad arms, with their relatively large surface area might have been a specific adaptation to quiet water environments where supplies of suspended particulate food was low. *Petalocrinus* may have also avoided areas subject to heavy sedimentation, since the arms were not capable of infolding and were thus susceptible to clogging of the ambulacra by sediment.

In the Glenwells Shale, camerate crinoids are present. They had flexible columns and at least in the mature stage lacked terminal holdfasts, and were secondarily attached by means of modified dististeles. Their arms were finely pinnulate with narrow ambulacral grooves and it is likely that camerates fed primarily on relatively small phytoplankton adopting a rheophilic filtration fan manner of feeding similar to that observed in modern crinoids. Kammer (1982) postulated that finely pinnulate forms should typify high-energy settings whereas crinoids with open meshed filtration fans should be more abundant in low-energy environments. This is not always the case. Many crinoids with open mesh filters occur exclusively in sediments associated with high-energy environments, and in the course of this investigation finely pinnulate camerates have been collected from the siltstones of the Glenwells Shale, which are low-energy sediments. The crinoids in the Rough Neuk Starfish bed were found with arms stretched out suggesting that burial occurred suddenly and rapidly.

Lowenstam (1957), used calyx structure as a means of differentiating crinoid associations of quiet waters from those characteristic of rough water stages of reef successions. Robust, heavily plated calyces are characteristic of higher energy environments, because the compact, thick-walled thecae afforded greater protection against being torn apart by water turbulence or by collision with other subjects. The columnals of Silurian crinoids may also display environmental responses in terms of thickness as Brett (1984), observed a two fold increase in mean columnal diameter in reef-dwelling crinoids from moderate and high energy settings. The fragile, thinly plated structure of the crinoids in the Rough Neuk Starfish bed is fully consistent with a quiet-water environment.

9.2.11 Starfish

Asteroids are marine benthonic echinoderms, living at all depths from the intertidal to the abyssal. They have colonised most available substrates. Four modern orders have been widely recognised following Perrier (1875). These are as follows: Paxillosida, Yalvatida, Spinulasida, and Forcipulatida. The classification of Palaeozoic forms is still under review.

Most modern starfish are predators and feed on molluscs, particularly preying on bivalves by stomach eversion but it is generally agreed the Palaeozoic asteroids probably could not evert their stomachs, precluding them from feeding extra-orally. Most Palaeozoic asteroids lived on soft substrates and ingested food directly; they seemingly had a much narrower range of life habitats than post-Palaeozoic taxa. They are preserved only because they were buried in place, and the absence of bivalves in the associated fauna is consistent with their interpretation as sediment ingesters rather than carnivores.

Clark (1912) and Ladd (1957) found Devonian bivalves and asteroids on the same bedding surface, and concluded that fossil starfish were specialist predators on bivalves and like present day starfish, could feed extraorally. There is no proof that asteriid type bivalve predation was taking place, in fact many of the asteroids appear inverted, suggesting that the bivalves and asteroids were juxtaposed by a current carrying the sediment (Gale 1987). In the Rough Neuk Starfish beds where the starfish are not inverted, and are found in situ.

9.2.12 Trace Fossils

Trace fossils are particularly important in sedimentary rocks because 1) by nature they must be autochthonous; they are destroyed by physical disturbances and post depositional transport. Cases of reworked worm tubes are extremely rare and easily recognisable; 2) they may occur in lithologies which are devoid of body fossils; 3) the trace reflects the behavioural response of an organism to a specific set of conditions, reflecting palaeoenvironmental conditions and thus the trace fossil morphology is more strongly controlled by the behavioural than by the anatomical characteristics of the producer, and 4) the morphological adaptations to burrowing are functionally and structurally similar to those of many extant phyla.

Generally protective burrows (deep, vertical) and resting tracks are prominent in shallow water environments, feeding burrows (horizontal, often branching or winding) prevail in the intermittent zone and patterned grazing tracks are found in the deepest zones (flysch-like sedimentation) Seilacher (1967).

This relationship forms the basis of Seilacher's (1967) bathymetric zonation of trace fossil communities. Moving offshore the communities are: *Scoyenia*, *Skolithos* and *Glossifungites*, *Cruziana*, *Zoophycos* and the *Nereites* facies.

The trace fossils in the Mulloch Hill Group consists of Domichnia (dwelling structures) and bioturbation. The straight vertical burrows are characteristic of *Skolithus* zone (Plate 7.9). The burrows were produced within the sediment by organisms pushing aside or excavating material, and were either used for dwelling or feeding purposes.

Full relief bioturbation (Seilacher, 1953, 1964a, b) is concentrated in one unit only exposed at locality 41. The cohesiveness of the sediment determines the ease with which an animal burrows as well as the permanence of that burrow. Furthermore the depth of the burrow is dependant upon interstitial water for respiration and the porosity of the sediment Boucot (1981), and all these parameters are determined in part by environmental conditions.

9.3 FOSSIL ORGANISM INTERRELATIONS

Interactions between and within species impart biological structure to an ecosystem and one function of palaeoecology is to try to determine the web of such interaction. In the Mulloch Hill Group and throughout the Craighead and Girvan shore sections, however, there is little evidence of organism interrelations in the fossil assemblages.

9.3.1 Encrustation

The main form of biotic interaction recorded in the Mulloch Hill Group fossil associations is encrustation by bryozoans. The ceramoporid cystoporate bryozoans tend to encrust the external surfaces of brachiopods, orientated in their current-stable orientations, suggesting that the host specimens were probably dead prior to encrustation and that rates of sedimentation were slow (Plate 9.1). Such occurrences however are rare. Double walled bryozoans such as ceramoporids are dependant on large, firm substrates, and their colonies would withstand considerable wave and current action. According to Kluge (1975) and Brood (1976) the ceramoporids are morphologically adapted to occur in shallow agitated waters as well as at greater depths.

9.3.2 Predation

Potential predators in the Silurian fossil assemblages include gastropods, cephalopods, echinoderms, and crustaceans, but because of the destructive nature of predation, evidence of predation in the fossil record is generally lacking (Bishop, 1975).

Evidence of predation and destruction by parasitism or commensalism in the form of boreholes in shells is relatively rare, in both the Craighead and Coastal Sections. Two brachiopod valves and a gastropod display rather convincing boreholes (Plate 9.1.1-3).

9.4 SUMMARY

Generally the fauna from the Mulloch Hill Group is characteristic of a shallow marine environment. In particular, the bryozoans, corals and algae are typical of well oxygenated environments of low to moderate rates of sedimentation, within photic zone and generally less than 100 metres in depth. The brachiopods and gastropods lived mostly on relatively hard substrata, in clear waters. Quiet water environments are also favoured by the *Petalocrinus* which would have clogged up in heavy sedimentation. Most of the brachiopods, gastropods and crinoids were deposit or suspension feeders, indicating a high ambient productivity.

These faunas which had established themselves in quiet waters, drifted after death on the sea floor and were then rapidly buried.

The Rough Neuk Starfish bed contains an in situ fauna. The starfish and crinoids probably lived in a shallow water low-energy environment, with a well oxygenated sea floor, and were suddenly and rapidly buried.

9.5 DISCUSSION OF FOSSIL COMMUNITIES AND DEPTH

In their study of brachiopod-dominated faunas from the Lower Silurian of Wales Ziegler et al. (1968) proposed an onshore-offshore model of five recurrent 'communities', each named after a typical species. These five 'communities' occur in concentric bands parallel with the shoreline and Ziegler et al. believed that they were related to water depth and distance from palaeoshoreline. Since then many workers have adopted Ziegler et al.'s communities as baythemetric standards, for Silurian community studies. For instances Johnson (1977) employed the communities to determine changes in sea level and Anderson (1971), used them to indicate tectonic setting.

Although these early studies acted as a basis for all later work there has been much subsequent discussion as to their validity and global applicability especially since subsequent research expanded geographically and stratigraphically beyond the Lower Silurian of Wales. Distributions of species in modern seas are determined by physico-chemical and biological factors. Benthic communities can occur in depth related arrays when the factors controlling distribution parallel bathymetry. Whereas in the geological past, distributions of fossil communities were controlled by similar factors to those of today, many of these remain elusive and it is hard to establish, in the case of the Welsh Silurian, what the controlling factors were and whether or not they paralleled bathymetry. Depth-related controls of distribution alone may not have been the only important factors. Complex interactions of other physical variables in the coastal environment such as substrate conditions, and availability of food may be equally important influences, as voiced by Makurath (1977). He further argues that recurrent communities demonstrate a higher level of regulation through species interdependence than environmental control, thus urging re-evaluation of the Ziegler model in terms of depth control.

In the Girvan district, the depositional environment was one of complex depositional processes in which the original palaeocommunities were transported and mixed. This together with non-preservation of the soft-bodied component precludes an analysis of their nature and diversity. Furthermore the brachiopod associations in the Mulloch Hill Formation do not exhibit the change in brachiopod fauna which would be expected with a gradual increase in depth. In the Mulloch Hill Group, Cocks & Toghill (1973) recognise a change in the brachiopod associations from a low diversity *'Cryptothyrella'* Association to high diversity *'Cryptothyrella'* Association through to a *Clorinda* Association, and finally to the graptolite faunas of the Glenwells Shale. As discussed in Chapter 8, *Cryptothyrella angustifrons* has been re-assigned to *Hyattidina*? *angustifrons*. If the *Hyattidina* Association equates with the *Eocoelia* 'Community' (Benthic Assemblage 2) and the *Clorinda* association represents Benthic Assemblage 5, then it appears that Benthic Assemblages 2 & 3 are missing (namely the *Pentamerus* or equivalents and *Stricklandia* Communities).

Unfortunately the *Stricklandia* specimens figured in Plate 8 though occurring in lithologies characteristic of the Mulloch Hill Formation, were found as loose specimens. Possibly the apparent absence of these missing Benthic Assemblages is related to the lack of exposure, and they may yet be found after further excavations have been made.

Cocks & Toghill (1973) also recognise a change from the *Stricklandia* into the *Clorinda* Community, in the Woodland Formation. But here not only are the first three Benthic Assemblages missing in the sequence, but there is substantial evidence that the brachiopods have been at least locally transported (see Chapter 7).

The use of Ziegler's depth related community concept in this instance, to indicate a transgressive sequence at the base of the Silurian seems rather inappropriate and cannot be accepted in full.

Plate 9.1 (Chapter 9)

Plate 9.1

MULLOCH HILL FORMATION

Figures 1-3 Bores in Fossils

1. Bore hole in brachiopod pedicle valve, lateral view, TW.32.141 x 4
2. Bore hole in brachiopod pedicle valve, lateral view, TW.89.142 x 6
3. Bore hole in a gastropod shell, TW.74.143 x 6

Figures 4-5

4. Sponge attached to pedicle valve of a brachiopod, TW.89.144 x 4

WOODLAND FORMATION

5. Sponge attached to a disarticulated brachiopod valve, locality 234, Scale : 10p coin.

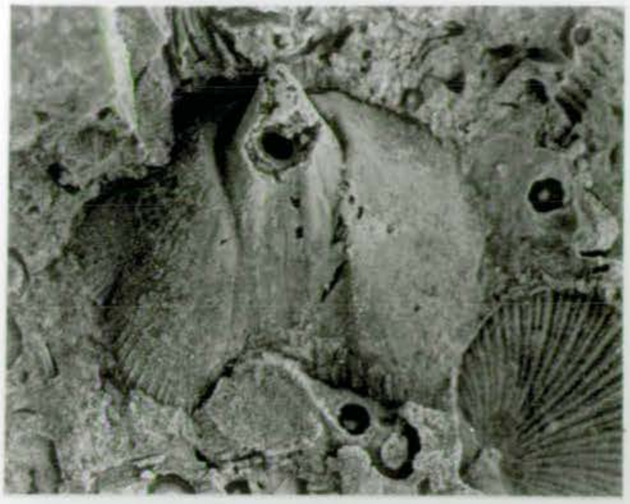
GLENWELLS SHALE FORMATION

Figures 6-7 Encrustation by bryozoan

6. Bryozoan encrustating a brachiopod, latex mould TW.52.145 x 4
7. Bryozoan encrustating a brachiopod, TW.52.145 x 5

PLATE 9.1

1



2

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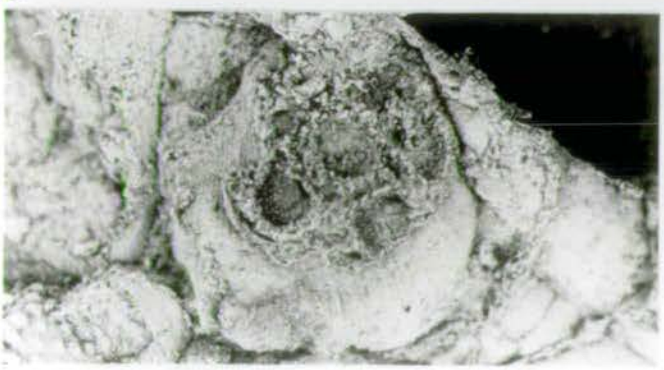


7

CHAPTER 10

10 PALAEOENVIRONMENTAL SYNTHESIS

10.1 INTRODUCTION

Of the Silurian Inliers of the Midland valley, only the Girvan district contains Silurian sediments older than the Upper Llandovery - as indicated by the representative graptolite faunas of all the Llandovery zones from *cyphus* to *crenulata* inclusive (Cocks & Toghill, 1973). In fact the most stratigraphically complete section showing the Ordovician - Silurian junction is found in the Craighead Inlier, where the succession contains a wide variety of siliclastic sediments, together with locally diverse shelly and graptolite faunas.

Unfortunately, palaeoenvironmental interpretations of the sediments of the Craighead Inlier and the Girvan Shore sections are limited owing to poor exposure, particularly in the case of the northeastern part of the Craighead Inlier, where it proved impossible to dig a trench. Consequently, field relations are not always obvious and lateral lithofacies variations are difficult to assess. In addition there is a general lack of sedimentary structures suitable for measuring palaeocurrent directions.

Despite these problems it has still proved possible to establish a general palaeoenvironmental picture, by synthesising all the available data. The two study regions, namely the Craighead Inlier and the Girvan Shore, are interpreted as the deposits of two separate submarine fan systems - each sequence representing a series of overlapping lobes in which both lateral and downflow transitions into sandstones and finer sediments are evident. Both sections, moreover, shared the same general provenance.

10.2 CRAIGHEAD INLIER

10.2.1 <u>The Ordovician - Silurian Boundary</u>

The highest Ordovician strata of the Craighead Inlier, namely the High Mains Sandstones, show changes in grain size, bedding and faunal composition indicative of a minor regression (Harper, 1988). This may have been a response to the glacio-eustatic event occurring towards the end of the Ordovician (Brenchley & Newall, 1980). This regression was associated with the cooling of the surface waters and to the drainage of broad continental shelves, and was followed by a rapid rise in sea level at the beginning of the Silurian, (Sheehan, 1977).

Overlying the highest Ordovician strata, the Mulloch Hill Conglomerate marks the base of the Silurian and is seen to both overstep and overlap the Ordovician sediments in a southerly and southwesterly direction (Cocks & Toghill, 1973; Harper, 1988).

10.2.2 Mulloch Hill Conglomerate Formation

The Mulloch Hill Conglomerate is characterised by poorly-sorted pebble- to cobble-conglomerates interbedded with very coarse- grained, grey-red coloured, laterally discontinuous lithic arenites. Lack of internal organisation of the conglomerates suggests rapid deposition by debris flows, whereas the sandstones were deposited by sheet floods.

Undoubtedly the sandstones were deposited in marine conditions since they contain a marine fauna, albeit almost exclusively composed of brachiopods and of very low diversity, found in the thinly-bedded sandstones which occur in the middle of the Formation. The presence of well-developed, low-angle and trough cross-bedding, the alignment of pebbles parallel to bedding, and the irregular bases and sharp tops of the sandstones all suggest deposition in relatively shallow water.

The base of the Mulloch Conglomerate oversteps and overlies two Ordovician Formations in the Craighead Inlier. The gradual reduction in clast size and bed thickness of the conglomerate from base to the top of the Formation records the gradual infilling of a large erosional channel. The laminated medium-grained lithic arenites containing discontinuous pebbly horizons and fossil fragments may represent the products of high density turbidity currents where finer-grained particles settled out.

Most of the brachiopods are disarticulated and badly fragmented, as are the crinoids and trilobites. Although these have clearly been transported, they may not have come from far away and all these species are typical of shallow water environments.

Palaeocurrent measurements from cross-bedding show that the source of the sediments lay approximately to the northwest. The varied composition of the clasts in the conglomerates indicates a wide provenance; they range through basic to intermediate igneous rocks, granite, low-grade metamorphic rocks and sedimentary rocks, such as fine-grained siltstones. A large drainage basin with diverse bed-rock lithology may be postulated.

The large size of some of the cobbles, up to 14 cm in diameter, suggests that the clasts were deposited relatively near to their source, a view supported by the abundance of large granite cobbles and the relatively high feldspar content in the chemically immature lithic arenites.

10.2.3 Mulloch Hill Formation

The Mulloch Hill Formation conformably overlies the Mulloch Hill Conglomerate and is characterised by poorly-sorted, fine-grained, purple- and green-coloured lithic arenites, siltstones and shales. The sandstones are laterally continuous, consistent in thickness, and display very faint grading which suggests that the sediments were deposited by successive currents in which deposition was accompanied by decreasing flow. The faunal composition is typical of shallow water environments. These sediments are interpreted as turbidites, though in fact they have very few features diagnostic of typical turbidites, for example 1) the general lack of cross-laminated Tc units which may be due to either the absence of the necessary grain size or high velocities causing the ripples to be planed out, and 2) the absence of sole markings (indicating that a cohesive mud substrate was lacking). The underlying Mulloch Hill Conglomerate was deposited by debris flows evolving into, and succeeded by, high density turbidity currents, and it is concluded that the sediments of the Mulloch Hill Formation, following the same sedimentary pattern, were also deposited by high density turbidity currents.

The lower and middle members of the Mulloch Hill Formation were deposited in fairly shallow water, between the weathering wave-base and scouring wave-base. The dominance of disarticulated brachiopods orientated convex-up and geopetal structures reveals that, after death and disarticulation, the valves of the brachiopods drifted along the sea floor. Those which remained articulated occasionally accumulated sand within their valves, and were rapidly buried by a sudden influx of sand.

Towards the top of the Formation there is a gradual increase in the diversity of the fauna, marked by the occurrence and increased abundance of trilobites, gastropods, bivalves and cephalopods, yet brachiopods are always dominant. The finer-grained sediments of Rough Neuk appear to have been deposited in slightly deeper water.

Since the majority of the fossils occur in distinctive shell lags where most multi-element organisms such as crinoids and trilobites are disassociated, and where most brachiopods are disarticulated with slightly unequal pedicle to brachial valve ratios, it is concluded that the fossils have experienced some pre-depositional drifting on the sea floor, or local transportation prior to deposition. In either case, the composition of the original community would have been modified to some degree and therefore it is here preferred to redefine and rename the *Cryptothyrella* Community, as recognised by Cocks and Toghill (1973), as the *Hyattidina* Association, naming the association after the most abundant brachiopod species. This Association also includes trilobites, crinoids, rugose corals and bryozoans as minor constituents.

One of the unexpected discoveries of this investigation was the Rough Neuk Starfish Bed, which yielded exquisitely preserved complete crinoids and starfish as well as dendroids, which are fairly rare in the fossil record. This bed represents an obrution deposit. Clearly the fauna has not been transported, but was catastrophically engulfed by a cloud of mud which smothered the organisms and blocked up the ambulacral systems of the echinoderms. The fauna must have been buried instantly to a depth from which escape was impossible. Both the crinoids and starfish lived on a relatively soft substrate in a low energy environment.

10.2.4 Glenwells Shale Formation

The overlying Glenwells Shale is divided into lower light-grey coloured fine-grained siltstones, middle unfossiliferous mudstones, and an upper pale-blue shale member. While the lack of sedimentary structures limits interpretation, the mudstones were probably deposited by relatively weak turbidity currents or suspension flows, with the finer fractions settling out. Accompanying a vertical change in lithofacies, there is a marked change in the composition of fauna from a faunal assemblage of moderate diversity (including brachiopods, trilobites, gastropods, crinoids and ostracods) at the base, into an assemblage of graptoloids from the upper shale member. This would accord with a transition from a shallow marine shelf environment to quieter, deeper water conditions. The brachiopod fauna, however, rather than displaying a smooth transition changes abruptly. At the top of the Mulloch Hill Formation the author found a high diversity *Hyattidina?* Association, correlating with Benthic Assemblage 2 of Boucot's (1975) bathymetric zonation, while a *Stricklandia* Association correlating with Benthic Assemblage 4/5, has come from the base of the Glenwell Shales. Benthic Assemblage 3 (*Pentamerus* Association) thus appears to be unrepresented. This could be related to the poor exposure alone, or it may on the other hand suggest that *Hyattidina?* was a pioneer opportunist with a broad potential for colonisation.

In the overall perspective, the thinning- and fining-upward sequence traced from the Mulloch Hill Conglomerate through the Mulloch Hill Formation to the Glenwells Shale is a result of fan-aggradation. The Mulloch Hill Conglomerate is interpreted as representing the filling of an erosional channel. Coarse-grained material would have been sporadically trapped in it when the channel was active. Deposition prevailed when the channel shifted flow and a new channel was cut. As the section of the fan gradually shallowed and widened and correspondingly the volume of flow decreased, the beds became much thinner- and finer-grained, as seen in the Mulloch Hill Formation. Eventually the channel became choked, as represented by the accumulation of the Glenwells Shale, and was finally abandoned.

10.2.5 Newlands Formation

The Newlands Conglomerate Member marks the base of the Newlands Formation. This pebble conglomerate is poorly sorted, and the general lack of both internal organisation and of bedding indicates that the conglomerates were rapidly deposited by thick debris flows. The relative thinness and small lateral extent of the conglomerate suggests that the sediments are the product of a small erosional channel building out from the original fan system into deeper water following rejuvenation in the source area.

No palaeocurrent data is available due to the lack of suitable sedimentary structures. The maximum size and compositional range of the clasts is, however, appreciably less than in the stratigraphically lower Mulloch Hill Conglomerate. In the Newlands Conglomerate Member the clasts are no more than 8 cm in diameter, and the granites and other diverse igneous and metamorphic lithologies present in the Mulloch Hill Conglomerate are here lacking. Change in the direction of the source area or dramatic changes in the composition of the source area are not considered likely because the two conglomerates in Glenwells Burn contain a higher compositional diversity of clasts, and the yellow luminescing epidotes match with those found in the Mulloch Hill Conglomerate. It is assumed therefore that the Newlands conglomerates were derived from the same source but deposited further away from it; the mineralogically unstable pebbles having disintegrated during transportation.

Interpretation of the two conglomerates exposed in Glenwells Burn is limited, owing to lack of exposure. Variations in the colours may be due to differential weathering in the burn. Thin cracks in many of the pebbles and matrix indicate post-depositional compaction.

The conglomerates of Glenwells Burn fine upwards into burrowed, bioclastic yellowish-brown coloured fine-grained sandstones and siltstones of the higher part ofthe Newlands Formation. Owing to poor exposure, lack of obvious bedding and sedimentary structures, palaeoenvironmental interpretation is tentative. Nevertheless, the poor sorting probably indicates that the sediments were rapidly deposited, and the sediment-water interface must have been well oxygenated in order to accommodate burrowing organisms.

Containing the only shelly Middle Llandovery rocks in the whole of the Girvan district, or indeed, as far as is known, in Scotland, the Newlands Formation is of great palaeontological interest. Furthermore, the fossil assemblages, which according to Cocks & Toghill (1973) belong to the *Stricklandia* and *Clorinda* 'Communities', overly the deep water graptolitic facies of the Glenwells Shale, indicating a minor regression.

10.2.6 Glenshalloch Shale Formation

The Glenshalloch Shale is subdivided into three members: lower light-blue coloured shales; banded shales; and upper shales interbedded with fine-grained quartz arenites. The banded shales display sedimentary structures diagnostic of thinly bedded Td-Te turbidites, such as small-scale load casts and flute and tool marks, all developed on the soles of the beds. The pale blue-green, fine-grained unfossiliferous shales were deposited by low velocity flows of the turbid mud. The light olive-grey coloured, coarser-grained laminae, containing brown organic flasers and graptoloid fragments, represent the settling of the finer fractions.

The fissility in the shales is primarily due to the original horizontal alignment of particles but has been preserved as a result of the absence of infauna in the original mud. The environment of deposition of the Glenshalloch Shale is thus envisaged as being abiotic, the result of bottom stagnation under the stratified water column. The fauna, exclusively composed of graptolites, contrasts with that in the underlying shelly Newlands Formation, indicating that after the short regressive phase during the deposition of the lower part of the Newlands Formation there was a return to a transgression. This transgression is associated with the gradual drowning of the minor channel.

Towards the top of the Formation there is a gradual increase in the sandstone - shale ratio and the succession develops into a coarsening and thickening upward sequence, where Tc-Td Bouma sequences are observed. The sandstones are moderately sorted and are almost exclusively composed of quartz with some mica. The presence of thinly bedded turbidites suggests that the sediments were deposited more distally from the source. A slight change in the source area, or a mixing of source areas, is indicated by the appearance of green-luminescing apatites.

10.2.7 Saugh Hill Grit Formation

The base of the Upper Saugh Hill Grit is marked by a poorly-sorted, quartz-rich pebbly sandstone. Since quartz is very resistant to wear and decomposition, the pebbly sandstones were probably formed by the gradual reduction of gravels of varied composition down to the most stable constituents.

The rest of the formation consists of thickly-bedded, green coloured coarse- to medium-grained lithic arenites, with sporadic pebbly horizons. Sedimentary structures and sole markings are typical of thickly bedded turbidites, as deposited by high density turbidity currents.

The coarsening and thickening upwards sequence traced from the top of the Glenshalloch Shale through to the base of the Upper Saugh Hill Grits records the aggradation of the channel system.

10.2.8° Pencleuch Shale Formation

No permanent exposure of the Pencleuch Shale was found during this investigation. The Pencleuch Shale is characterised by grey-brown shales intercalated with siltstones yielding an abundant graptoloid fauna (Cocks & Toghill, 1973). The dark colour of the shales and the abundance of graptoloids would suggest that the conditions were anoxic, and that the sediment was deposited in fairly deep water. As a result of the complete lack of exposure, palaeoenvironmental inferences are tenuous.

10.2.9 Lower Camregan Grit Formation

Overlying the Pencleuch Shale is the Lower Camregan Grit Formation. This is very poorly exposed, and consists of purple coloured coarse-grained sandstones with occasional conglomeratic horizons (Cocks & Toghill, 1973). As well as a pronounced change in sediment-type, the graptoloid fauna of the Pencleuch Shale is replaced by a shelly fauna in the overlying Lower Camregan Grits, with brachiopods characteristic of an *Eocoelia* Association and succeeding *Pentamerus* Association (Cocks & Toghill, 1973), and trilobites typical of shallow marine conditions.

Unfortunately the junction between the Pencleuch Shale and Lower Camregan Grits is not exposed.

10.2.10 General synthesis of the Craighead Inlier

The succession in the Craighead Inlier shows three successive phases of thinning and fining upwards (Fig. 10.1a) These are primarily related to autocyclic phases of submarine fan progradation and aggradation, when lobes of the original fan shifted laterally and built out during progradation and then became choked up during aggradation before they were finally abandoned. It is fully realised that much more work is required before a proper interpretation of the Silurian successions at Craighead, at the coast, and in Penwhapple Burn can be made. In the meantime the proposed model for the Mulloch Hill Group, as summarised in Fig. 10.1b, is felt to be consistent with the evidence so far gathered.

Cyclic transgressions and regressions are likewise recorded by the alternating shelly and graptolitic faunas in the finer and coarser sediment respectively. For example a phase of transgression is recorded from the Mulloch Hill Conglomerate to the Glenwells Shale, reflected by

Fig. 10.1 A summary diagram of the Silurian succession in the Craighead Inlier. Mulloch Hill Conglomerate Formation (M.H.C.Fm.), Mulloch Hill Formation (M.H.Fm.), Glenwells Shale Formation (G.S.Fm.), Newlands Conglomerate Member (N.C.), Newlands Formation (N.Fm.), Glenshalloch Shale Formation (Gl.S.Fm.), Upper Saugh Hill Grit Formation (U.S.H.G.Fm.), Pencleuch Shale Formation (P.S.Fm.), and Lower Camregan Grit Formation (L.C.G.Fm.)
For other abbreviations see Fig. 10.2.

FIGURE 10.1

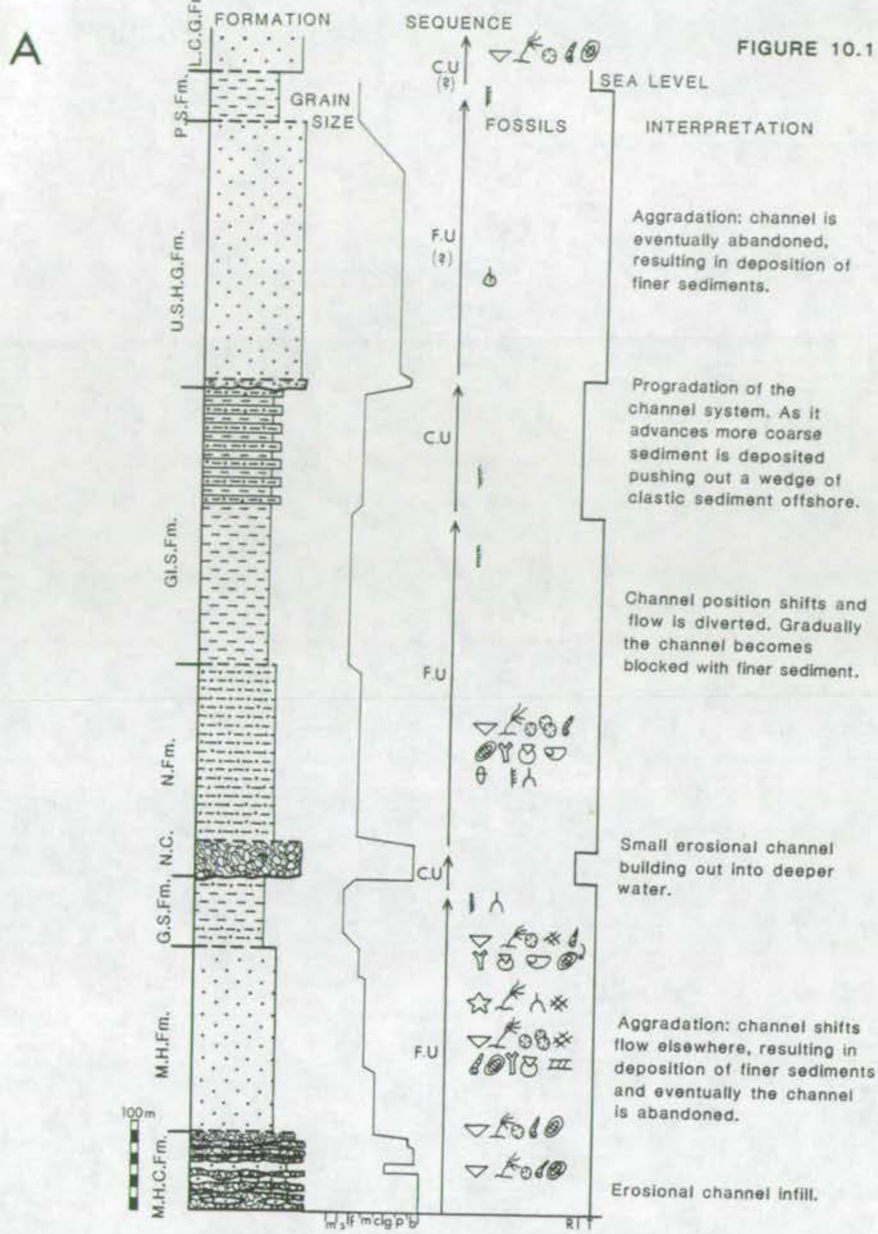


Fig (10.1 A) Summary diagram of the Silurian succesion in the Craighead Inlier.

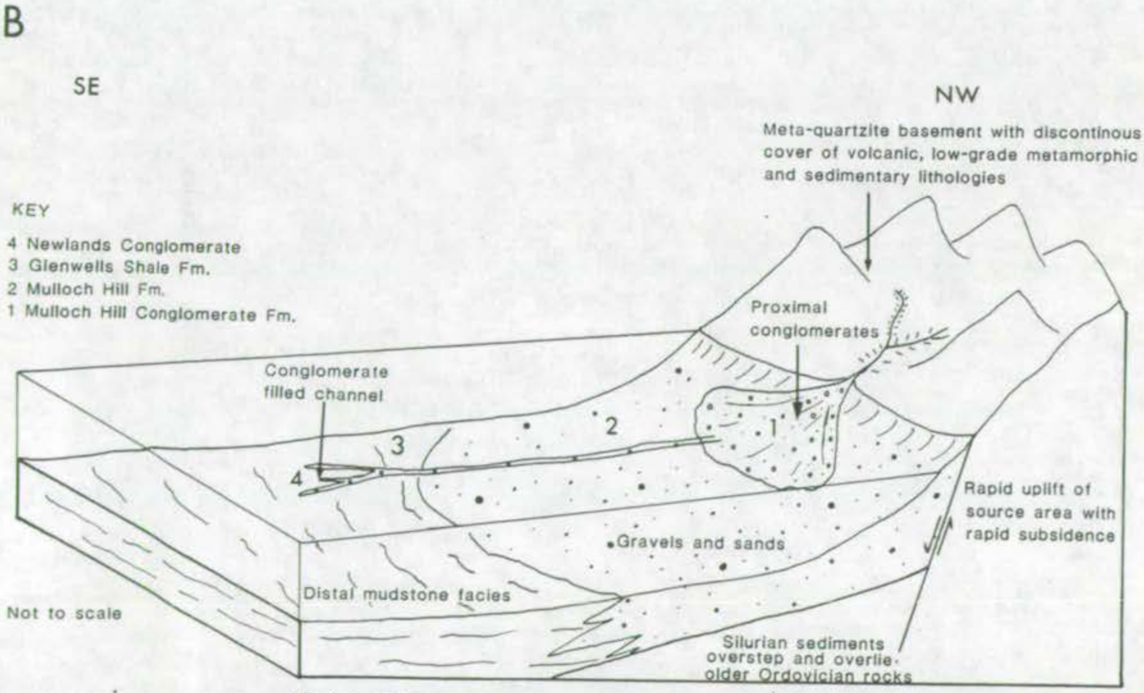


Fig (10.1 B) Inferred depositional model for the Mulloch Hill Group, Craighead Inlier.

the increase in the diversity of the fauna, the change in the Benthic Assemblage from 2-4, and finally the deposition of shales containing graptolites. The overlying Newlands Conglomerate records a phase of progradation when a minor lobe built out, and is associated with a shallowing of the water depth and a return to a shelly fauna characteristic of Benthic Assemblage 4/5. This episode was only short-lived as the lobe gradually shifted, and there was a return in the Glenshalloch Shales to shales yielding graptolites, indicative of deeper water. Towards the top of the Glenshalloch Shales, however, the sequence coarsens and thickens upwards again into the Upper Saugh Hill Grits indicating a slight lowering of the sea level. No depth-related fossils were found, but this may only reflect the return to greater water depths. Finally, in the overlying Lower Camregan Grits which contain a shelly fauna characteristic of Benthic Assemblage 2, an *Eocoelia* Association is juxtaposed against the graptoloid-bearing shales, and this marks the final regression in the highest Silurian strata in the Craighead Inlier.

Sea level curves for the Silurian sequences of the Scottish Midland Valley, Ireland and America have been compiled by McKerrow (1979), and more recently this has been slightly modified by Williams and Harper (1988) who demonstrate a correlation between South Mayo and Girvan. A late Llandovery marine transgression at Girvan is closely followed by a similar event in South Mayo. Furthermore, the effects of a basal Wenlock regression are evident in both areas. Williams and Harper conclude that these events are comparable yet slightly diachronous, reflected also in similar sedimentary facies where the initiation of the transgression is represented by shallow marine fossiliferous sandstones fining upwards into deep shelf, poorly-fossiliferous red or purple mudstones.

10.3 COASTAL SECTION; THE HAVEN AND WOODLAND POINT

10.3.1 Craigskelly Conglomerate Formation

On the Coast, the junction between the Ordovician and Silurian is represented by an unconformity at the base of the Craigskelly Conglomerate. The poorly-sorted, pebble- supported pebble to boulder conglomerates are interbedded with laterally discontinuous coarse-grained lithic arenites.

Lack of internal organisation within the conglomerates at Craigskelly indicates that the conglomerates were deposited rapidly by debris flows, whilst the sandstones were the products of high density turbidity currents. Reverse- and normal-grading displayed at the Haven exposures represent transitions from traction to suspension flows. The conglomerates were fairly erosive, as indicated by the presence of pale green mudstone clasts of these sediments derived from the underlying soft substratum. Deposition of these sediments seems to have taken place in relatively shallow water because of the presence of laminated sandstones, and the gradational bases and sharp tops of the sandstone units.

Cobbles as large as 78 cm diameter, and the high percentage of chemically unstable constituents such as granite and feldspar, suggest that the conglomerates were not deposited far from the source, and the source area provided an abundant range of igneous, metamorphic and sedimentary rocks. Palaeocurrent directions indicate a source to the northwest.

10.3.2 Woodland Formation

The breccia at the base of the Woodland Formation on Craigskelly is composed of angular pebbles of dolomite, quartz, chert and a few igneous clasts. This breccia fines upwards into medium light-grey coloured siltstones containing a very sparse graptoloid fauna.

At the Haven, laminated mudstones of the Woodland Formation are overlain by three low, rugged exposures composed of dolomitised limestone. Bedding within the limestone is obscured, and the limestone contains shallow marine brachiopods and compound corals, juxtaposed with the underlying and overlying mudstones containing graptolites. The overlying shales are much affected by syn-sedimentary deformation, and the presence of fine parallel striations on the limestones suggest that these same limestones are allochthonous, having slid down as blocks, into their present position.

The overlying laminated shales in the Haven are typical of thinly bedded Tc-Td Bouma sequences which accumulated in an environment far away from the source. The silty laminae are the products of small-scale, low density turbidity currents, whilst the much finer muds were deposited by settling out of suspension. Soft sediment deformation at or near the sediment-water interface includes slumping, flame structures, dewatering effects, boudinage structures and small-scale folds and microfaults. These shales are thrown into tight, disharmonic folds that are clearly truncated by the overlying conglomerate.

At Woodland Point, however, the lowest exposures of the Woodland Formation are composed of alternating fossiliferous mudstones interbedded with very fine-grained sandstones with a calcareous cement. Lateral continuity of the strata, alternations of coarse- and fine-grained beds, and low angle cross-bedding are diagnostic of Tc-Td Bouma sequences, as produced by low density turbidity currents. Previously Ziegler et al. (1966) described a block recovered from these exposures in which articulated brachiopods were found in life positions. During this investigation over a thousand samples were measured for orientation studies, and only 2% of the brachiopods were found to be articulated. Thus it can only be concluded that the block described by Ziegler et al. (1966) was an exceptionally rare occurrence. The dominance of concave-up valves indicates generally quiet water settings where the shells were intermittently stirred up from the sea floor, followed by gravity settling.

These thinly bedded turbidites are overlain by laminated shales (Td-Te turbidites) containing a sparse graptolite fauna. Unlike those at the Haven, these laminated shales do not appear to have suffered syn-sedimentary deformation.

10.3.3 Haven Conglomerate

Locally developed, the poorly-sorted pebble to cobble Haven Conglomerate forms the base of the Scart Grits, and at the Haven the base unconformably overlies the Woodland Formation. Internal organisation in the conglomerate is lacking, and bedding is poorly developed, so therefore the conglomerates were probably deposited rapidly by debris flows. The clasts are generally of low sphericity, angular to subrounded, and the clast composition is not as diverse as in the underlying Craigskelly Conglomerate. Quartz clasts are dominant, with minor amounts of lavas, chert, dolerite, red jasper and dolomites.

The bioclastic siltstone pebbles were derived from the underlying Woodland Formation. A significant time-lapse must be envisaged for the unconformity at the base of the Haven Conglomerate to allow for the partial lithification of the Woodland Formation shales, and for syn-sedimentary deformation. Subsequently the lithified substratum was eroded and the underlying shales were ripped up and were incorporated in the rapidly deposited conglomerate. During the associated stratigraphical break there may have been a minor phase of uplift associated with rejuvenation in the source area.

The change in the composition of the pebbles, particularly the change in luminescing colours of the apatite from yellow to green, may be related to a change in the location of the source area. Bluck (1983) gave evidence for a palaeocurrent trending northeast-southwest, and it is possible that by this stage detritus was derived dominantly from the northeast rather than northwest. Furthermore, the appearance of dolomite pebbles and cobbles is interpreted as indicating that the fan probably built out on the slope below a carbonate bank.

10.3.4 Scart Grit Formation

Poorly-sorted pebbly sandstones at the base of the Scart Grits, at Woodland Point, display reverse- and normal-grading and were deposited by sandy high density turbidity currents which formed debris flows. Within these units three stages of formation can be detected; 1) traction sedimentation, 2) traction carpet and 3) suspension. Where some of the bases show scour marks the current may have been locally erosive. In the upper parts of the sandstone the dish-and-ball structures are products of fluidisation, post-depositional structures resulting from excess pore-waters rising upwards and disrupting the laminations.

The rest of the sediments within this Formation resemble typical Ta-Tb-Tc Bouma sequences and, accordingly, were deposited further from the source area. They do not, however, represent typical distal turbidites. Palaeocurrent directions derived from the flute marks, and measurements of cross-bedding, indicate a source which lay to the northeast, just as has been deduced from the underlying Haven Conglomerates. This source area was rich in dolomite, crinoidal limestones, green apatite, and extrusive igneous lithologies.

Although no fossils were observed in the field, fragmented brachiopod valves which appear to have been transported were detected by cathodoluminescence.

10.3.5 General synthesis of the coastal section

The succession at the coast shows two phases of thinning and fining upwards. Initially the large erosional channel represented by the Craigskelly Conglomerate shifted laterally and built out during progradation, and then became filled during aggradation when the finer material of the Woodland Formation settled out (Fig. 10.2). During this time, blocks of limestone slid down the continental slope, and the sediments at the Haven were subjected to syn-sedimentary deformation.

A second phase of progradation then occurred, when a small erosional channel built out onto deeper water, represented by the Haven Conglomerate, and the overlying Scart Grits record the later aggradation. In association with progradation, the level of sea water may have fallen slightly.

The introduction of dolomite and crinoidal limestone pebbles may be related to the change in the situation of the source area, which lay to the northwest during deposition of the Craigskelly Conglomerate, and then moved to the northeast during deposition of the Haven Conglomerate and Scart Grits.

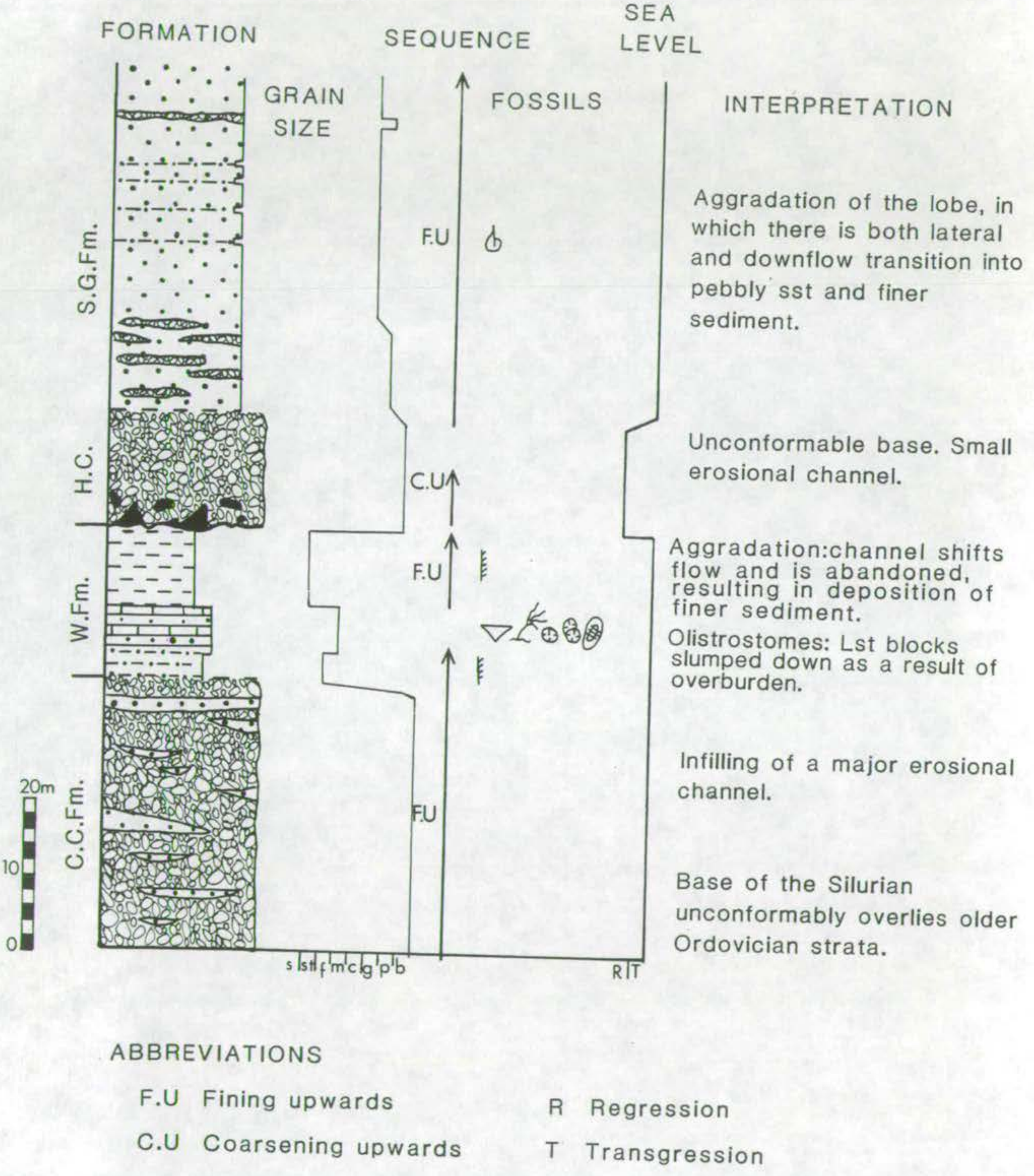
10.4 BIOSTRATIGRAPHICAL AND LITHOSTRATIGRAPHIC CORRELATIONS

10.4.1 Biostratigraphical correlation of the Craighead Inlier and coastal section

The brachiopods from the Mulloch Hill Formation (Craighead) appear to be younger than the oldest Llandovery A_1-A_2 faunas of Haverfordwest Meifod, and Llandovery (Temple, 1987). Cocks and Toghill (1973) conclude that the Mulloch Hill Formation is likely to correlate with A_3 or the lower part of A_4 in the type Llandovery area, giving it an upper Rhuddanian age, and consequently the underlying Mulloch Hill Conglomerate Formation is probably of about middle Rhuddanian age (Fig. 10.3).

According to Cocks and Toghill (1973), the Mulloch Hill Conglomerate is in fact older than the Craigskelly Conglomerate on the coast, which is dated as approximately Upper Rhuddanian age, biostratigraphically correlating with the lower part of the Mulloch Hill Formation, whilst the upper half of the Mulloch Hill Formation is thought to correlate with the shelly lower Woodland Formation, on the coast (Cocks & Toghill, 1973).

Fig. 10.2 Summary diagram of the Silurian succession at Girvan. Craigskelly Conglomerate Formation (C.C.Fm.), Woodland Formation (W.Fm.), Haven Conglomerate Member (H.C.), and Scart Grit Formation (S.G.Fm.)



Fig(10.2) Summary diagram of the Silurian succesion on the Girvan shore.

In the Craighead Inlier the Glenwells Shale contains an upper *cyphus* zone graptolite fauna which can be easily correlated with the upper Woodland Formation of the coastal section.

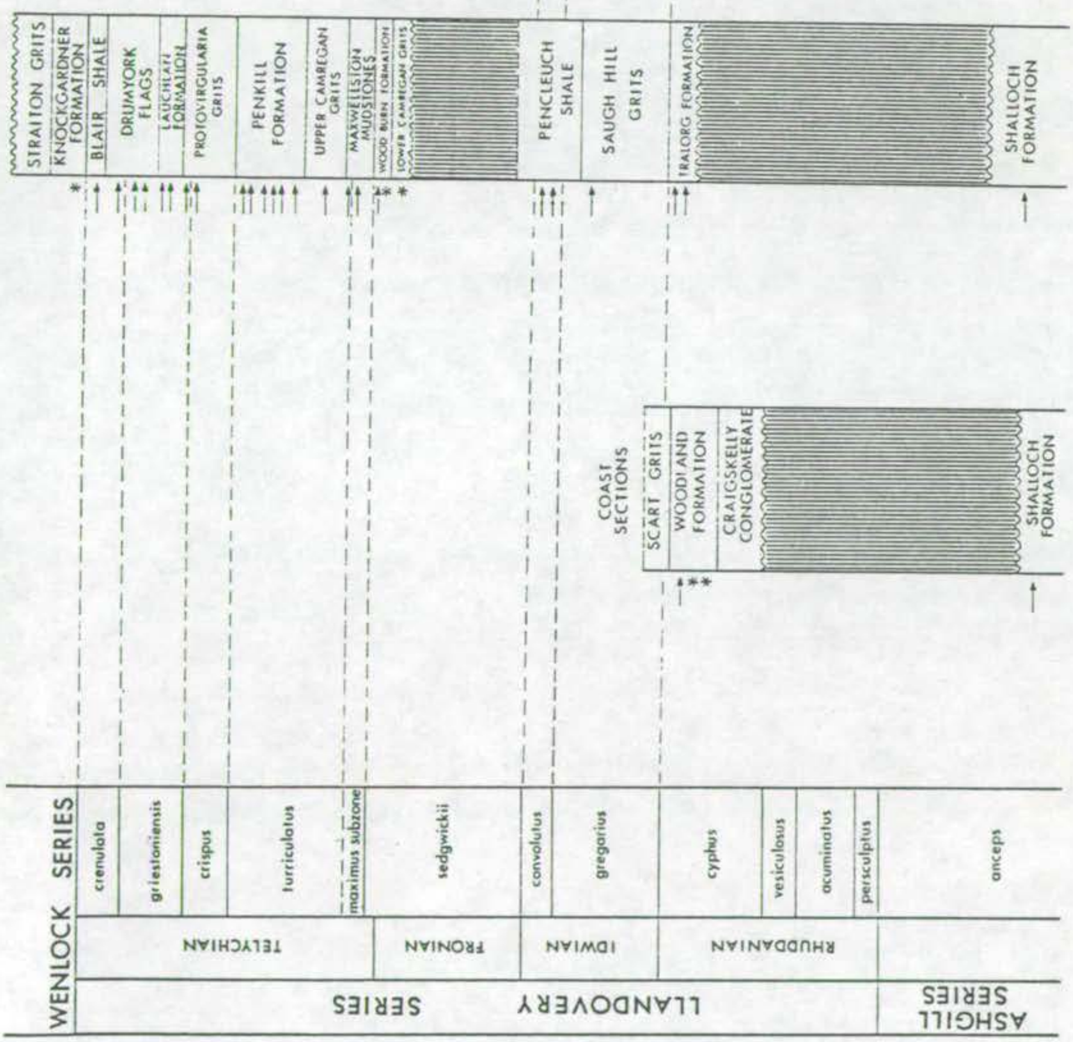
The Newlands Formation is dated by Cocks and Toghill (1973) as post upper *cyphus* zone, and pre the *gregarius* zone (*magnus* subzone) fauna of the Glenshalloch Shale and consequently the Newlands Conglomerate - Newlands Formation in the Craighead Inlier is correlated with the Haven Conglomerate and Scart Grits at the coast. However, the base of the Haven Conglomerate is clearly unconformable and there must be a stratigraphical hiatus at this level. Unfortunately no diagnostic fossils were found, therefore the conglomerate and the overlying sandstone of the Scart Grits which constitute the highest Silurian Formation in the coastal sequence, cannot be dated, and consequently the magnitude of the stratigraphical break cannot be estimated.

10.4.2 Biostratigraphical correlation of the Craighead Inlier and coastal section with Penwhapple Burn

All the graptolite zones from *cyphus* to *crenulata* are exposed in the Main Outcrop along the Penwhapple Burn (Fig. 10.3). In addition to the numerous graptolite localities in most of the Formations, there are at least four Formations containing shelly faunas. The succession basically consists of series of alternating sandstones, shales and mudstones.

The base of the Silurian, in Penwhapple Burn, is represented by the Tralorg Formation and the junction between the Tralorg Formation and the underlying Shalloch Formation (Ordovician) is apparently tectonised (Harper, 1988). The Tralorg Formation is characterised by grey-brown mudstones, black pyritic, graptolitic mudstones and grey shales yielding a *cyphus* zone graptolite fauna which correlates with both the Glenwells Shale, and the top of the Woodland Formation.

The overlying Saugh Hill Grits consist of massive sandstones with sporadic pebbly horizons sometimes exclusively composed of quartz. Load structures are present on the soles of the beds. Graptolites found near the top of the Formation give a *gregarius* zone age which correlates with the Newlands Conglomerate - Newlands Formation sequence in the Craighead Inlier and the Haven Conglomerates and Scart Grit Formation of the coastal section.



Fig(10.3) Biostratigraphical correlation of the Silurian of Girvan. Taken from Cocks and Toghill (1973).

In Penwhapple Burn, the Saugh Hill Grits contain a 60-100 metre mudstone member which Cocks and Toghill (1973) suggest thickens to the northeast to become the Glenshalloch Shale of the Craighead Inlier. Graptolites from the Glenshalloch Shale indicate the *magnus* subzone of the *gregarius* zone, but graptolites from the mudstone member are too fragmentary to be identified.

The overlying horizon which by correlation with the Main Outcrop (Cocks & Toghill, 1973) is referred to as the Pencleuch Shale, is not permanently exposed in the Craighead Inlier. In the Main Outcrop it is characterised by a lower highly contorted grey shale unit and an upper black shale unit, containing large calcareous nodules. The abundant graptolite fauna belongs chiefly to the *convolutus* zone with only a single recorded fragment of *M. sedgwickii* to indicate any higher horizon, and graptolite faunas from the 'Pencleuch Shale' of the Craighead Inlier found by Cocks and Toghill (1973) are also typical of the upper *convolutus* zone.

A stratigraphical break is inferred at the junction between the Pencleuch Shale and the Lower Camregan Grit Formation. The brachiopods, in particular *Eocoelia curtisi*, from the Lower Camregan Grits, in both the Main Outcrop and the Craighead Inlier, indicate a correlation with the very top of the *sedgwickii* zone, Aeronian age (Cocks, 1971), whereas in the underlying Pencleuch Shale only a single fragment of *M. sedgwickii* was found (Cocks & Toghill, 1973). Therefore there is a gap in the fossil record of most of the *sedgwickii* zone. Owing to lack of exposure, it is impossible to say whether or not the stratigraphical break is represented by an unconformity, however in Penwhapple Burn the junction is seen to be cut by the Camregan Fault.

The Lower Camregan Grits represent the highest Silurian beds exposed in the Craighead Inlier, but in the Main Outcrop a further 1500-2000 m of strata occur above this level in Penwhapple Burn, where the graptolite zones from *cyphus* to *crenulata* are exposed.

10.4.3 Lithological Correlation of the coastal sections with the Craighead Inlier

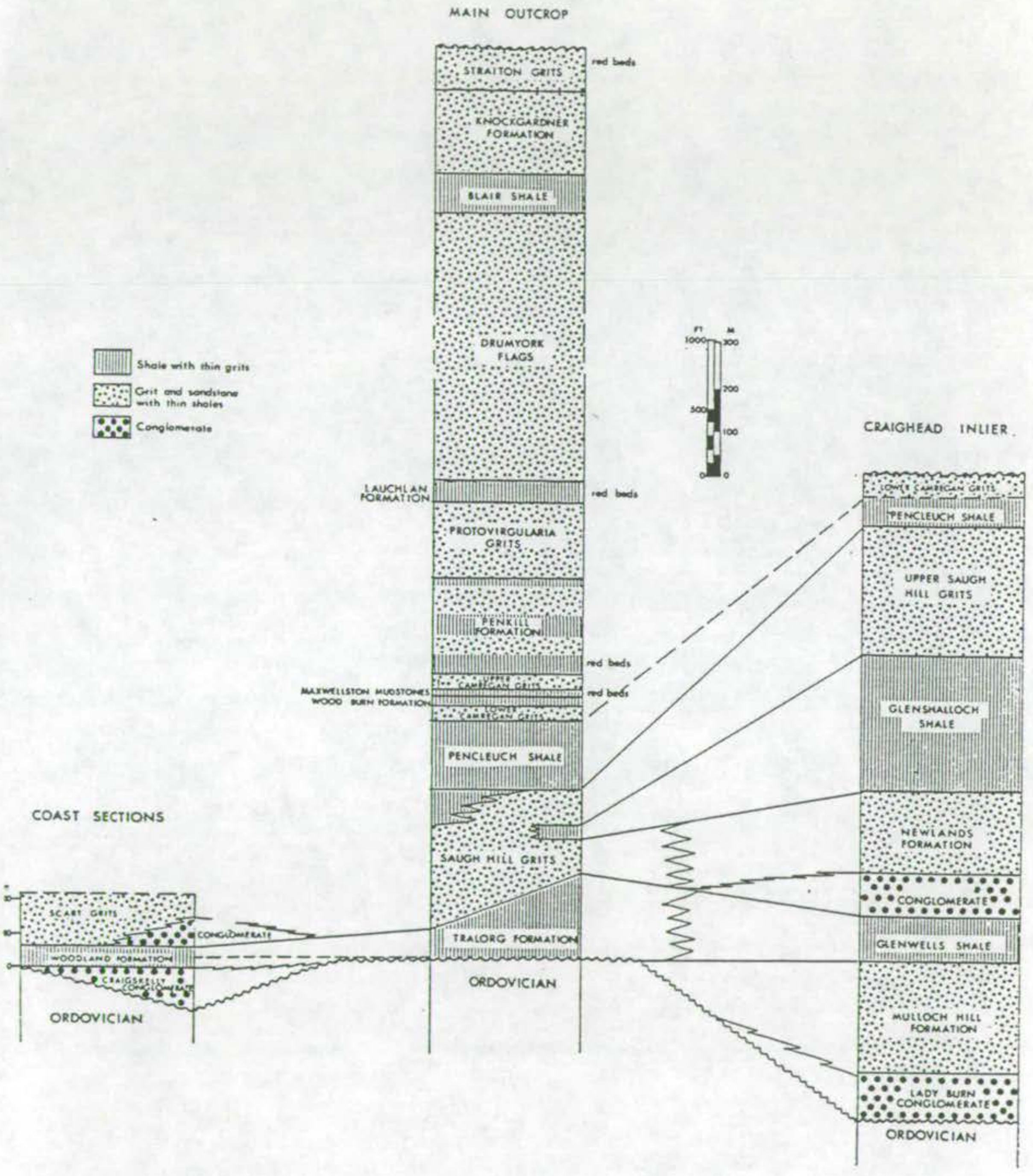
Both the Mulloch Hill and Craigskelly Conglomerates were deposited by similar sedimentological processes, namely debris flows producing a sequence of poorly-sorted clast-supported conglomerates interbedded with laterally discontinuous coarse-grained lithic arenites.

According to biostratigraphical correlations, however, the Mulloch Hill Conglomerate Formation is older, of *acuminatus* age, whilst the Craigskelly Conglomerate Formation is dated as of *cyphus* age, and was thus deposited approximately at the same time as the Mulloch Hill Formation, from the Craighead Inlier.

Further differences include colour, maximum clast-size, bed thickness, development of normal- and reverse-grading, and clast composition, all of which have been discussed in Chapter 4. Although both conglomerates share the same general palaeocurrent directions, indicating a source to the northwest, quartz is more abundant in the Mulloch Hill Conglomerate, and reworked conglomerate clasts and shale clasts are lacking. These differences in clast composition may reflect different palaeogeographies. It appears that the two conglomerates were possibly deposited in the same basin but in two separate areas within it (Fig. 10.4).

This model would account for the other differences in the lithologies of the various Formations in the two areas. For example, despite the occurrence of siltstones in the lowermost parts of the Woodland Formation which resemble those of the Glenwells Shale, and the similarity in benthic assemblages, (*Stricklandia* and *Clorinda* Associations), there are also pronounced differences. The Woodland Formation contains limestone blocks which appear to have slumped down, fine-grained sandstones alternating with fossiliferous mudstone units, interpreted as thinly bedded turbidites, and mudstone/siltstone turbidite couplets. None of these sediments are represented in the Glenwells Shale and on these grounds the Woodland Formation does not correlate well lithologically with the Glenwells Shale.

The Haven and Newlands Conglomerates are probably of equivalent age and both were deposited by debris flows producing very thickly bedded, poorly-sorted conglomerates. Clasts within the Haven conglomerate are much larger and are of more varied composition as compared with the Newlands Conglomerate of the Craighead Inlier. The former conglomerate contains clasts ripped up from the underlying Formation, and large dolomite clasts are abundant. The most parsimonious explanation is that differences in clast composition reflect a rather lithologically varied hinterland and may also indicate that the successions at the coast and in the Craighead Inlier were deposited in two separate areas along the



Fig(10.4) Lithostratigraphical correlation of the Silurian of Girvan. Taken from Cocks and Toghill (1973).

same basin. The coastal section may represent a second submarine fan within this basin, deriving its sediments from the northwest.

10.4.4 Correlation of the Other Midland Valley Inliers

As previously mentioned in Chapter 1, Silurian rocks are exposed in seven other Inliers in the Midland Valley of Scotland (Fig. 10.5). These inliers expose rocks ranging in age from Llandovery to possible Ludlow (Cocks et al., 1971). In general they comprise of grey marine sediments including turbidites which are nearly always followed by red beds, containing mud cracks and fining-upward cycles, and are interpreted as lacustrine, inter-tidal and fluvial deposits (Walton, 1983; McGiven, 1976; Mitchell & McKerrow, 1975). Walton (1983) provides an up-to-date account of the stratigraphy of the various Inliers.

Lithological correlation between the Silurian Inliers of the Midland Valley is still rather tentative because defined formations vary in thickness within individual inliers (Rolfe, 1961) and often formations do not have counterparts in other inliers (Jennings, 1961). There are, however, two laterally persistent bands occurring in the Wenlock which have been used for more widespread correlations: 1) the Igneous Conglomerate, and 2) the Quartzite Conglomerate, both of which have been previously discussed in Chapter 4.

The Igneous Conglomerate occurs low in the Wenlock (Rolfe & Fritz, 1966; cf Cocks et al., 1971) and is exposed in the Hagshaw Hills (Parishholm Conglomerate), at Carmichael (Fence Conglomerate) and in the Pentland Hills (Igneous Conglomerate). Bluck (1983) demonstrates that both the lower Llandovery Conglomerates at Girvan, and the basal Wenlock and Igneous Conglomerates in the other Midland Valley inliers are rich in high-acidic rock fragments. The stratigraphically higher Quartzite Conglomerate of mid-Wenlock age (Cocks et al., 1971) is also exposed in the Hagshaw Hills (Hareshaw Conglomerate), at Lesmahagow (Middlefield Conglomerate), at Carmichael (Kirkhill Conglomerate) and also in the Pentland Hills (Quartzite Conglomerate), though in the Pentlands it is very thin.

McGiven (1967) and Bluck (1983) consider the Igneous Conglomerate to be lithologically similar throughout the Midland Valley, representing a single laterally extensive conglomeratic horizon; the Quartzite Conglomerate also represents a single thick horizon.

Fig. 10.5 Stratigraphic correlation of Silurian sediments across the Midland Valley of Scotland.

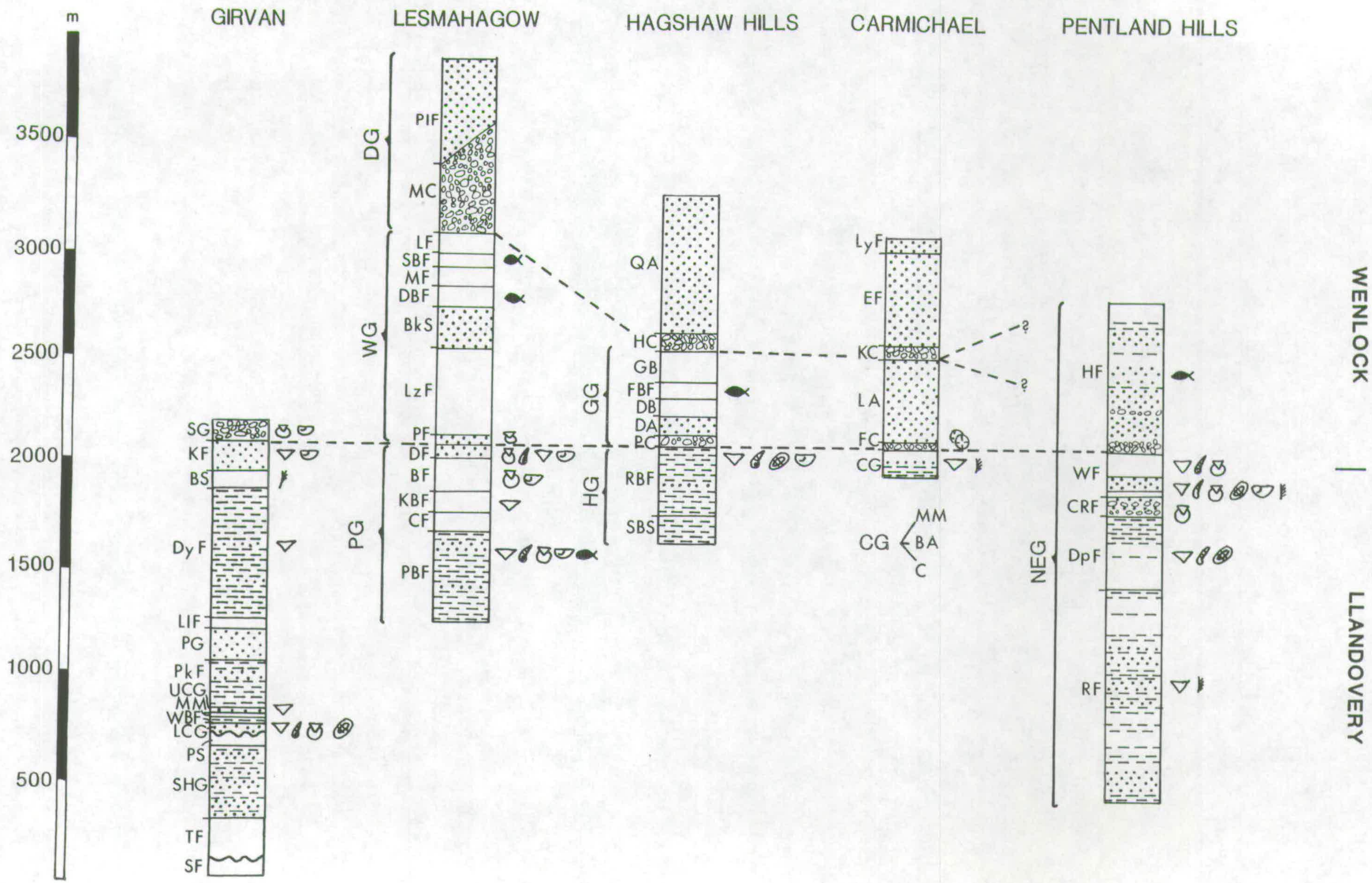
Girvan: Blair Shale (BS), Drumyork Flags (DyF), Knockgairdner Formation (KF), Lauchlan Formation (LlF), Lower Camregan Grits (LCG), Maxwellston Mudstones (MM), Pencleugh Shale (PS), Penkill Formation (PkF), Protovirgularia Grits (PG), Saugh Hill Grits (SHG), Shalloch Formation (SF), Straiton Grits (SG), Tralorg Formation (TF), Upper Camregan Grits (UCG), Wood Burn Formation (WBF).

Lesmahagow: Birkenhead Sandstone (BkS), Blaeberry Formation (BF), Castle Formation (CF), Dippal Burn Formation (DBF), Dungavel Group (DG), Dunside Formation (DF), Kip Burn Formation (KBF), Leaze Formation (LzF), Logan Formation (LF), Middle Field Conglomerate (MC), Monument Formation (MF), Passage Formation (PF), Patrick Burn Formation (PBF), Plewlands Formation (PF), Priesthill Group (PG), Slot Burn Formation (SBF), Waterhead Group (WG).

Hagshaw Hills: Douglas Water Arenite (DA), Dovestone Red Beds (DB), Fish Bed Formation (FBF), Glenbuck Group (GG), Gully Red Beds (GB), Hagshaw Group (HG), Hareshaw Conglomerate (HC), Parishholm Conglomerate (PC), Quarry Arenite (QA), Ree Burn Formation (RBF), Smithy Burn Siltstone (SBS).

Carmichael: Burn Bridge Arenite (BA), Carmichael Burn Group (CG), Crossridge Formation (CF), Eastgate Formation (EF), Fence Conglomerate (FC), Kirkhill Conglomerate (KC), Lochlyoch Formation (LyF), Manse Mudstone (MM), Newside Arenite (NA).

Pentland Hills: Cock rig Formation (CRF), Deerhope Formation (DpF), Henshaw Formation (HF), North Esk Group (NEG), Reservoir Formation (RF), Wether Law Linn Formation (WF).
See Figure 2.3 for key to log symbols.
Modified from Craig (1983).


m
3500
3000
2500
2000
1500
1000
500
GIRVAN
LESMAHAGOW
HAGSHAW HILLS
CARMICHAEL
PENTLAND HILLS
SG
KF
BS
Dy F
LIF
PG
Pk F
UCG
MM
WBF
LCG
PS
SHG
TF
SF
DG
WG
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CF
PBF
QA
HC
GB
FBF
DB
DA
PC
RBF
SBS
GG
HG
LyF
EF
KC
LA
FC
CG
CG
MM
BA
C
?
?
HF
WF
CRF
DpF
RF
NEG
WENLOCK
LLANDOVERY

FIGURE 10.5

Only these two horizons can be traced for any distance, and the finer-grained sediments show such pronounced local facies variation between the different areas, that lithological comparison is hindered. Consequently, any lithological correlation of the finer-grained sediments can only be based upon broadly equivalent groups or formations, in association with the two well-defined conglomeratic marker horizons (Fig. 10.5).

Biostratigraphical correlation is also rather tentative since the precise age of at least some of the Silurian sequences in the Midland Valley is still problematic, especially in the central Inliers. Graptolites, microfossils and brachiopods indicate an upper Llandovery age for the marine sequence in the Reservoir Formation, Pentland Hills (Bull, 1987), and the same chronostratigraphic level is indicated by abundant vomerinid graptolites in the Blair Shale (Girvan), possibly the Smithy Burn Siltstones (Hagshaw Hills), and the Carmichael Burn Group (Carmichael).

The highest strata underlying the Silurian red-beds in all the Midland Valley Inliers may be early Wenlock in age, and it is presumed that initial deposition of red-beds throughout the Midland Valley Inliers was approximately contemporaneous.

Fossils from below the Igneous Conglomerate in the Hagshaw Hills of possible Wenlock - Ludlow age have been discovered by Rolfe and Fritz (1966). In the continental sedimentary beds fish beds occur whose faunas can be roughly correlated between the Hagshaw Hills, Lesmahagow and the Pentland Hills.

10.5 REGIONAL SETTING

10.5.1 Source Areas

During the Llandovery the sediments deposited in the Girvan district had a broadly northern provenance. The Mulloch Hill Conglomerate in the Craighead Inlier and the Craigskelly Conglomerate in the Coastal section display similar palaeocurrent directions, with sediment derivation from the northwest. It is therefore assumed that the two areas initially shared the same provenance, though slight variations in clast composition may indicate somewhat different palaeogeographies.

On the coast there is, higher up in the sequence, a distinct change in palaeocurrent direction (the Haven Conglomerate and Scart Grits) from northwest to northeast (Bluck, 1983). This seems to be associated with the abrupt appearance of large dolomite and crinoidal limestone clasts and green-luminescing apatite. Palaeocurrent data for the top of the Craighead succession is lacking, yet here also, green-luminescing apatite replaces the yellow-luminescing apatite of the underlying Mulloch Hill Group. This may be either related to mixing of source areas or a slight change in the palaeocurrent direction.

In the Craighead Inlier there is a marked reduction in the diversity of pebble composition in the higher conglomerates. The Mulloch Hill Conglomerate is composed of plutonic and extrusive igneous clasts with minor amounts of metamorphic and sedimentary rock fragments - but the Upper Saugh Hill Grit pebbly sandstones are composed almost exclusively of the most resistant meta-quartzite pebbles. Likewise, in the conglomerates from the Hagshaw Hills, Carmichael and North Esk, early Wenlock Igneous Conglomerates are followed by younger Quartzite Conglomerates. This is probably unrelated since during the Wenlock their provenance was located in the south-southeast (Bluck, 1983, 1984). Recently, Heinz and Loeschke (1988) analysed thirty-four igneous clasts from the Parishholm and Hareshaw Conglomerates (Hagshaw Hills). Although both conglomerates were shed from the direction of the Southern Uplands into the Midland Valley, the geochemical composition of the clasts indicated different source areas; namely peralkaline rhyolites and calc-alkaline rhyolites. The latter are thought to have been derived from a volcanic terrane, situated during the Silurian in the area where the Southern Uplands are now. The geotectonic character of this terrane still remains uncertain.

The Silurian successions exposed in a number of Inliers in Ireland, occurring north of the supposed continuation of the Southern Uplands Fault, exhibit some similarities with the Girvan district and other Scottish Silurian Inliers. In particular, the upper Llandovery to basal Wenlock conglomerates of South Mayo are thought to have had a source which lay to the northeast (Williams & O'Connor, 1987; for references on stratigraphy see McKerrow & Campbell, 1960; Piper, 1972; Laird & McKerrow, 1970) and there is palaeocurrent evidence from higher up in the succession which indicates a northerly and northeasterly trending shoreline (Laird, 1969; Williams & Nealon, 1987). A northerly source is also envisaged for the Llandovery sandstones of Lisbellaw (Simon, 1986).

Both the Galway, Lisbellaw, and Pomeroy conglomerates are dominated by metaquartzite clasts and since metaquartzite-rich conglomerates are also common in the Scottish Silurian Inliers it is likely that these Inliers shared a common provenance, though the Silurian conglomerates were deposited in different sedimentary environments (Williams & Harper, 1988). These conglomerates record the proximal unroofing of a metaquartzite basement which had a discontinuous cover of non-metamorphosed volcanic, low-grade metamorphic and sedimentary lithologies, probably of Ordovician and early Silurian age (Williams & Harper, 1988).

Some of the igneous clasts in the Silurian conglomerates of the Midland Valley are thought to have been derived from approximately synchronous volcanically active sources. For example, Bluck's (1983, 1985) suggestion of an inter-arc environment for the Silurian of the Midland Valley implies that clasts might be derived from volcanic material of Silurian age. In all the Silurian Inliers, the earliest documented horizon for conglomerates derived from synchronous volcanic sources is from the Mulloch Hill Conglomerate (Middle Rhuddanian), in the Craighead Inlier. Elsewhere in the Midland Valley sequences, there is little evidence of contemporaneous igneous activity. Tuffs are rare; the only records are the tuff bands in the North Esk Inlier of the Pentland Hills, noted by Tipper (1976), whilst interbedded lavas are absent. Thus it appears that the conglomerate clasts reflect the erosion of extinct late Ordovician to early Silurian volcanic edifices which, since the Lettergesh Formation of the Galway sequence records deposition proximal to an active volcanic source (Williams & Harper, 1988), appear to have migrated northwestwards with time.

10.5.2 Regional setting

The evolution and tectonic setting of the Midland Valley during the Silurian has been the subject of much debate. It has been suggested that the area may have developed as an accretionary prism (McKerrow et al., 1977; Leggett et al., 1979a, b, 1982) yet recently it has become apparent that this is not accepted by all workers. One of the first to express doubts about this model was Moseley (1977, 1978) who believed that the Iapetus ocean had closed by the end of the Ordovician and subsequently had difficulty in accepting the concept of Silurian subduction of ocean floors. Pickering, Bassett and Siveter (1988), however, present evidence suggesting that by the late Ordovician - early Silurian times the ocean had only partially closed, although marine seaways persisted until the middle or late Silurian. Furthermore, Walton (1983) noted that the structure, facies-distribution and stratigraphic relationships are more complex than first envisaged in 1977.

Most recently, Williams and Harper (1988) demonstrate similarities in provenance-type, sedimentary facies development and fossil assemblages of the Silurian Inliers of the Scottish Midland Valley with those in South Mayo, western Ireland, suggesting that these sequences represent sediment accumulations in a single, albeit partly fragmented basin (Fig. 10.6). Both Silurian sequences lay on the northern margins of the closing Iapetus Ocean, yet palaeontological evidence demonstrates an earlier transgressive event at Girvan than South Mayo, indicating that part of western Ireland lay northwest of Girvan during the evolution of this basin.

Initiation of the basin is seen as extensional foundering of older Ordovician basin remnants. By *gregarius* zone time clasts were derived from a basement of Ordovician and older rocks, as well as from a region of active though decreasing Ordovician/Silurian volcanism in the south-east. A northwesterly marine transgression was initiated between the *sedgwickii* and *griestoniensis* zone which moved across an area of more uniform and slower subsidence. Finally by the *centrifugus* zone, tectonic inversion causing local uplift induced northward palaeocurrents in alluvial fans in the Scottish Midland Valley (Bluck, 1983), accompanied by volcanism adjacent to the sites of deposition in Western Ireland (Williams & Harper, 1988).

If the volcanic source migrated north-westwards with time, and volcanism was arc-related, then the basin may have contained a number of inter-arc sub-basins, according with Bluck's (1983) model which includes an inter-arc basin for the Silurian of the Midland Valley of Scotland. Similarly in Newfoundland volcanism in the Silurian successions is diachronous (Kennedy, 1979) and Williams and Harper (1988) demonstrate progressive northwesterly younging of volcanism across the whole belt of the axial zone of the Appalachian - Caledonian orogenic belt, when the earliest volcanism occurred in the Scottish Midland Valley and the latest in Quebec. Despite this apparent continuation of subduction

Locality abbreviations

N G North Galway

C H Charlestown

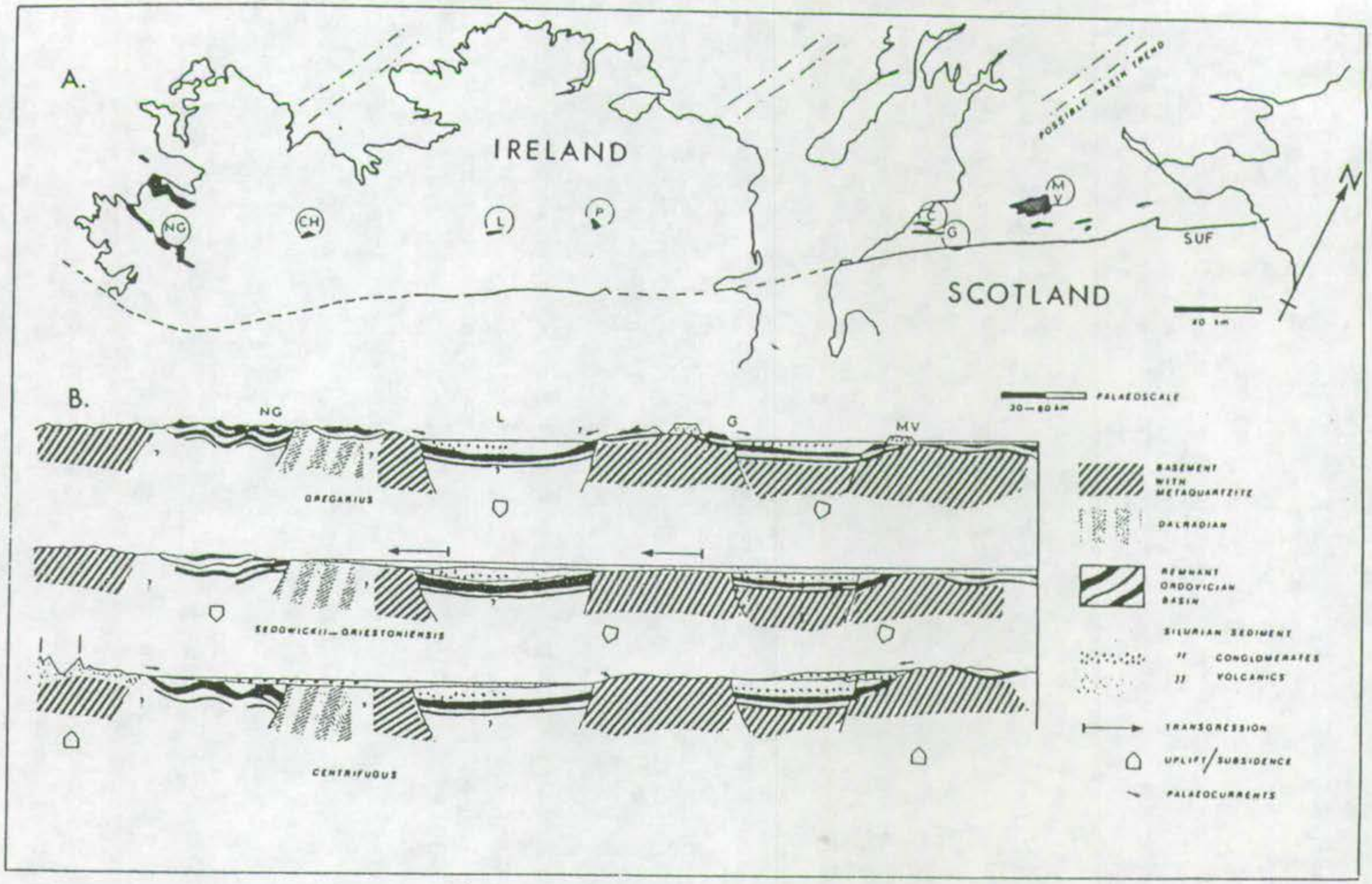
L Lisbellow

P Pomeroy

C Craighead

G Girvan (Main Outcrop)

M V Midland Valley



Fig(10.6)

(A) Map showing the present relationship of the Silurian succesions and indicating the approximate situation of sub-basins.

(B) Three time-slices through the proposed Silurian basins. Taken from Williams and Harper (1988).

during the Silurian, there is no certainty that volcanism was arc-related, as it may have been controlled by strike-slip faults.

It is now generally believed that subsidence of the various sub-basins was associated with block rotation. Bluck (1983) explains the southwesterly overlap and overstep of the basal Silurian facies at Girvan, during the Llandovery, as the result of deposition on blocks of Ordovician strata separated by high-angle listric faults with approximately east to west trends. Within the middle Ordovician succession of the Girvan district evidence of fault-controlled sedimentation has been documented by Williams (1962) and Ince (1984). It is thought that the basin floor behaved irregularly, with overall subsidence interrupted by periods of relative uplift. During extensional phases the relative downfaulting of blocks sequentially to the south may have resulted in the rotation of each block about an axis parallel to the east-west trend of the listric faults, resulting in the emergence of the apex of each block. Locally this would lead to regression and channel development (Harper, 1988). Such rotational subsidence would allow for concomitant submergence and emergence of different parts of the same block. Another example of fault-controlled sedimentary basins has been described from Silurian sequences on New World Island, Newfoundland (Arnott, 1983).

Before any general consensus can be reached on the evolution and tectonic setting of the Midland Valley of Scotland during the Silurian more field evidence is needed for the various Inliers (including the northeastern corner of the Craighead Inlier); and new fossil localities and revised taxonomy are vital for tighter biostratigraphic control. New and detailed studies on the sedimentology and sedimentary petrography combined with cathodoluminesence will aid environmental interpretations as well as the determination of the precise nature of the provenance, and this could be supplemented by radioisotopic dating of the granite and lava clasts. And finally, further work is necessary on determining the times of deformation in the individual tracts.

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APPENDIX 1

1. STRATIGRAPHIC DEFINITIONS OF THE FORMATIONS IN THE CRAIGHEAD INLIER AND GIRVAN COASTAL SECTIONS

1.1 CRAIGHEAD

1.1.1 Mulloch Hill Conglomerate Formation

Previous names: Mulloch Hill Conglomerate (Lapworth, 1882)
Mulloch Hill Conglomerate (Peach & Horne, 1899)
Mulloch Hill Conglomerate (Lamont, 1935)
Mulloch Hill Conglomerate (Freshney, 1959)
Lady Burn Conglomerate (Cocks & Toghill, 1973)
Mulloch Hill Conglomerate (Harper 198).

Characteristic lithofacies : Pebble to cobble sized polymictic conglomerates interbedded with very coarse-grained sandstones. Conglomerate beds occur up to 1.50 m thick, whilst sandstone beds occur up to 0.40 m thick. Sandstones show low angle cross stratification, trough cross bedding, and parallel laminations.

Base : Conglomerates overlying highest South Threave Formation (Ordovician), in Lady Burn (locality 73).
Top : not seen. Highest pebble conglomerate interbedded with coarse-grained sandstone (locality 4).

Type section: Above Quarrel Hill (locality 13).

Definitions of members: Upper. Pebble conglomerate interbedded with coarse-grained sandstones (locality 4).
Middle. Thinly bedded, medium-grained sandstone (locality 1)
Lower. Pebble and cobble conglomerates interbedded with coarse-grained sandstone (locality 13).

Other sections: Quarrel Hill (localities 1-12, 16, 17)
High Mains (localities 23-30, 91, 92)
Lady Burn (localities 70, 72, 73).

Estimated thickness : 90 m.

1.1.2 Mulloch Hill Formation

Previous names : Mulloch Hill Sandstone (Lapworth, 1882)
Mulloch Hill Sandstone (Peach & Horne, 1899)
Mulloch Hill Sandstone (Lamont, 1935)
Mulloch Hill Sandstone (Freshney, 1959)
Mulloch Hill Formation (Cocks & Toghill, 1973)

Characteristic lithofacies : Medium to thickly bedded dark yellowish brown to dusky-yellow coloured fine grained sandstones, alternate with siltstones. Sandstones occasionally show very faint parallel and cross laminations. In places paper thin dark yellowish-brown coloured shales developed.

Base : Lowest dark yellowish-brown coloured medium-grained sandstones, with shelly horizons developed (locality 22).
Top : Highest laminated and cross bedded fine-grained dusky yellow coloured bioclastic sandstones and siltstones (locality 89).

Type section : Rough Neuk Quarry (locality 89).

Definition of members : (3 members)
Upper. Dusky-yellow coloured, fine-grained bioclastic sandstones and siltstones, occasionally topped with paper shales (Rough Neuk, locality 89).
Middle. Greyish-red purple coloured, thickly bedded sandstones and siltstones. Moderately bioturbated and burrowed (Road section below Kirkhill, locality 41).
Lower. Alternating medium to thickly bedded dark yellowish-brown coloured, fine grained sandstones (locality 22).

Other sections :
Below Kirkhill (locality 32-51)
Below Kirkhill (locality 56-66)
(locality 74-78)
High Mains Wood (locality 85-90).

Estimated thickness : 220 m.

1.1.3 Glenwells Shale Formation

Previous names :
Glenwells Shale (Lapworth, 1882)
Glenwells Shale (Peach & Horne, 1899)
Glenwells Shale (Lamont, 1935)
Glenwells Shale (Freshney, 1959)
Glenwells Shale (Cocks & Toghill, 1973)

Characteristic lithofacies : Bioclastic medium grey coloured, siltstones and pale blue graptolite bearing mudstones.

Base : Lowest medium grey coloured, bioturbated bioclastic siltstones (locality 53).
Top : Highest medium-grained greyish-orange coloured quartz siltstones (locality 93).

Type section : Gully below Kirkhill (locality 52)

Definition of members : (4 members)
Top member 4) medium-grained greyish-orange coloured siltstones (locality 93)
3) Graptolite bearing pale blue mudstones (
2) Unfossiliferous pale blue mudstones (locality 84)
Basal member 1) Bioclastic medium grey coloured siltstones (locality 52).

Other sections :
Gully in Kirkhill (locality 52)
Glenwells Burn (locality 96, 97).

Estimated thickness : 80 m.

1.1.4 Newlands Formation

Previous names : *Pentamerus* Grits and Flags of Newlands (Lapworth, 1882)
Pentamerus Grits (Newlands) (Peach & Horne, 1899)
Newlands Ochreous Flagstones (Lamont, 1935)
Pentamerus Beds (Freshney, 1959)
Newlands Formation (Cocks & Toghill, 1973)

Characteristic lithofacies : Basal pebble conglomerate fines upwards into fine-grained moderate yellowish brown coloured sandstones and siltstones.

Base : Lowest poorly sorted pebble conglomerate having good pale red-purple colour, interbedded with discontinuous sandstone lenses (locality 94).

Top : Highest moderate yellowish-brown coloured bioclastic siltstones, moderately bioturbated and burrowed (locality 124).

Type section : Glenwells Burn (locality 99).

Definition of members : (4 members)

4) Top : Bioclastic siltstones (locality 125)
3) Glenwells Burn Conglomerate 2:
Pale brown coloured pebble conglomerate (locality 99)
2) Glenwells Burn Conglomerate 1:
Grey-olive coloured pebble conglomerate (locality 98)
1) Newlands Conglomerate:
Pale red- purple coloured pebble conglomerate (locality 55).

Other sections : In Glenwells Burn below locality 99
Northeast of Newlands Formation, locality 124.

Estimated thickness : 200 m.

1.1.5 Glenshalloch Shale Formation

Previous names : Glenshalloch Shale (Lapworth, 1882)
Monograptus gregarius Shale (Glenshalloch) Peach & Horne, 1899)
Monograptus gregarius Shale (Glenshalloch) (Lamont, 1935)
Monograptus gregarius Shale (Glenshalloch) (Freshney, 1959)
Monograptus gregarius Shale (Glenshalloch) (Cocks & Toghill, 1973)

Characteristic lithofacies : Laminated, fissile shales interbedded with thinly bedded faintly cross laminated light grey coloured siltstones.

Base : Lowest, fine-grained faintly laminated, pale blue shales (locality 126).

Top : Highest, light blue colo ed shales alternating with thinly bedded, faintly cross laminated fine-grained sandstone (locality 145).

Type section : Baldrennan Burn (locality 145).

Definition of members : (3 members)
Top: Shales interbedded with thinly bedded, fine-grained sandstones (locality 145)
Middle: Laminated, graptolite bearing shales (locality 129)
Lower: Pale blue shales (locality 126).

Other sections : Stream flowing perpendicular to Baldrennan Burn (locality 127, 128, 129, 130, 131)
Baldrennan Burn (locality 132-144).

Estimated thickness : 360 m.

1.1.6 Saugh Hill Grit Formation

Previous names : Saugh Hill Sandstones (Freshney, 1959)
Upper Saugh Hill Grit (Cocks & Toghill, 1973).

Characteristic lithofacies : Thickly bedded, coarse-grained, pale brown coloured sandstone, with sporadic pebble horizons.

Base : Lowest pebbly coarse-grained pale brown coloured sandstone (locality 146a)
Top : Not exposed.

Type section : Baldrennan Burn (locality 146)

Definition of members : (2 members)
Upper : Thickly bedded coarse-grained sandstones (locality 146b)
Lower : Basal pebbly sandstone (locality 146a)

Other sections : None

Estimated thickness : Aproximately 290 m.

1.1.7 Pencleuch Shale Formation

Previous names : *M. sedgwickii* Shales (Freshney, 1959)
Pencleuch Shale (Cocks & Toghill, 1973).

Characteristic lithofacies : Grey-brown shales alternating with siltstones (Cocks & Toghill, 1973).

Base : Not exposed.
Top : Not exposed.

Type section : Carscallan Cairn (NS 29370543) (Cocks & Toghill, 1973).

Other section: None.

Estimated thickness : Not possible.

1.1.8 Lower Camregan Grit Formation

Previous names : Camregan Group (Freshney, 1959)
Lower Camregan Grit (Cocks & Toghill, 1973)

Characteristic lithofacies : Purple coloured coarse-grained sandstones, occasionally interbedded with conglomeratic beds.

Base : Not exposed.
Top : Not exposed.

Type section : Craigfin Hill (NS 29410545) (Cocks & Toghill, 1973).

Other section: None.

Estimated thickness : Not possible.

1.2 GIRVAN SHORE

1.2.1 Craigskelly Conglomerate Formation

Previous names : Craigskelly Boulder Conglomerate (Lapworth, 1882)
Craigskelly Conglomerate (Peach & Horne, 1899)
Craigskelly Conglomerate (Cocks & Toghill, 1973)

Characteristic lithofacies : Poorly sorted pebble to boulder, polymict conglomerates interbedded with very- to coarse-grained, olive-green coloured laterally discontinuous sandstone beds.

Base : Poorly sorted pebble to cobble conglomerate unconformably overlying the highest Formation (Ordovician), at the Haven (locality 208).
Top : Poorly sorted pebble conglomerate (locality 204).

Type section : Craigskelly (locality 204).

Other sections: Craigskelly (locality 205, 207)
Horse Rock (locality 208, 211)

Estimated thickness: 38 m.

1.2.2 Woodland Formation

Previous names : Woodland limestone striped (Lapworth, 1882)
Woodland limestone and *Diplograptus modestus* and *Monograptus gregarius* shales (Peach & Horne, 1899)
Woodland Formation (Cocks & Toghill, 1973)

Characteristic lithofacies : Lithologies range from carbonate breccia, light grey coloured siltstones, dolomitised limestone, thinly bedded turbidites, and laminated shales yielding graptolites.

Base : Carbonate rich breccia overlies the Craigskelly Conglomerate at Craigskelly (locality 206).
Top : Laminated light grey and dark grey coloured shales, displaying microfaults, boundinages, slump structures, underly the Haven conglomerate (locality 215).

Definition of members : (5 members)
5) Laminated light grey and dark grey coloured shales (locality 215)
4) Alternating calcereous cemented siltstones and mudstones (locality 231)
3) Dolomitised limestone (locality 212)
2) Light grey siltstone (locality 206)
1) Carbonate rich breccia (locality 206)

Other sections : The Haven (locality 213, 214, 221)
Woodland Point (locality 229, 230, 232-235)

Estimated thickness : Minimum thickness 21 m.

1.2.3 Scart Grit Formation

Previous names : Quartz Conglomerate, Scart Grits and Flagstones (Lapworth, 1882) (Peach & Horne, 1899)
Scart Grits and Quartz Conglomerate (Cocks & Toghill, 1973)

Characteristic lithofacies : Pebble to cobble quartz rich conglomerate, containing ripped up clasts of the underlying Woodland Formation, at the base passing upwards into very coarse to coarse-grained thickly bedded sandstones. Soles of sandstone beds display load casts, flute clasts, also dish structures are present. Towards top, sandstones are interbedded with laminated siltstones.

Base : Poorly sorted quartz rich conglomerate unconformably overlies top of the Woodland Formation (locality 217).
Top : Highest coarse-grained, thickly bedded pale red coloured sandstones pass upwards into a pebbly light grey coloured sandstone (locality 227).

Type section : Woodland Point (locality 226)

Definition of members : (4 members)
4) Light grey coloured pebbly sandstone (locality 227)
3) Coarse-grained thickly bedded sandstones alternating with laminated siltstones (locality 226)
2) Thickly bedded coarse-grained sandstones containing sporadic pebbly horizons (locality 225)
1) Haven Conglomerate. Basal quartz rich pebble to cobble conglomerate (locality 217).

Other sections : Haven (locality 218, 224)
Woodland Point (locality 237, 239)

Estimated thickness : Minimum thickness 28 m.

2. RAW DATA FOR PEBBLE MEASUREMENTS

2.1 CRAIGHEAD INLIER

2.1.1 Mulloch Hill Conglomerate Formation

Table 1

	Maximum clast size			Shape				Roundness					Sphericity		
Unit	l	i	s	eq	tab	blad	rod	ang	suba	sr	r	wr	low	mod	high
Locality 13															
1.	6.1	5.5	4.6	-	4	7	4			2	11	2	11	4	-
2.	5.3	4.6	3.8	1	1	10	3			2	12	1	12	3	-
3.	2.6	2.2	1.7	2	2	4	7			-	14	1	12	2	1
4.	5.5	5.1	3.8	1	9	4	1			1	7	7	12	3	-
5.	1.9	1.6	1.3	6	6	3	-			3	7	5	3	11	1
6.	1.9	1.9	1.6	4	8	3	-			-	11	4	7	8	-
7.	3.7	3.4	2.9	1	6	3	5			-	10	5	8	7	-
8.	3.7	3.5	2.8	1	10	-	4			-	10	5	9	6	-
9.	2.9	2.6	2.0	4	7	4	-			-	11	4	6	8	1
10.	3.9	3.5	3.1	-	6	2	7			2	10	3	11	4	-
11.	2.5	2.3	1.6	1	10	2	2			-	8	7	10	4	1
12.	6.7	6.3	4.7	-	8	7	-			1	8	6	13	2	-
13.	5.8	5.2	3.9	-	5	6	4			2	7	6	11	4	-
14.	1.8	1.6	1.0	2	10	2	1			1	7	7	10	5	-
15.	6.3	6.2	4.7	-	9	5	1			1	8	6	6	9	-
16.	3.5	3.2	2.4	1	6	6	2			2	8	5	10	5	-
17.	3.8	3.7	2.6	3	11	1	-			-	9	6	9	6	-
18.	4.6	4.7	3.4	-	11	3	1			1	8	6	9	6	-
19.	5.1	5.0	3.9	-	9	4	2			1	7	7	7	8	-
20.	3.3	3.2	2.4	-	6	5	4			1	8	6	10	5	-
Total				27	141	80	52			20	181	99	189	107	4
Locality 6															
1.	3.3	3.0	2.4	-	11	2	2			-	9	6	8	7	-
Locality 7															
1.	3.4	3.3	2.3	-	14	1	-			1	4	10	8	7	-
2.	2.8	2.3	2.5	-	7	5	3			-	11	4	12	3	-

Table 1
Raw data collected from the Mulloch Hill Conglomerate Formation (locality 13, 6 and 7)
Abbreviations are as follows: l = long, i = intermediate, s = short diameters; eq = equant, tab = tabulate, blad = bladed, rod = rod shaped; ang = angular, suba = subangular, sr = subrounded, r = rounded, wr = well rounded; low, mod = moderate, high sphericity. N = 300.

Table 2

Unit %	Maximum clast size l	i	s	Shape eq	tab	blad	rod	Roundness ang	suba	sr	r	wr	Sphericity low	mod	high
1.	11.5	9.2	8.1	-	27	47	27			13	73	13	73	27	-
2.	8.7	6.7	5.4	7	7	67	20			13	80	7	80	20	-
3.	3.7	3.2	2.4	13	13	27	47			-	93	7	80	13	7
4.	10.6	9.8	8.4	7	60	27	7			7	47	47	80	20	-
5.	3.6	2.8	1.6	40	40	20	-			20	47	33	20	73	7
6.	9.5	9.4	8.2	27	53	20	-			-	73	27	47	53	-
7.	9.2	8.3	7.8	7	40	20	33			-	67	33	53	47	-
8.	5.0	5.4	4.8	7	67	27	-			-	67	33	60	40	-
9.	8.8	7.3	4.6	27	47	27	-			-	73	27	40	53	7
10.	3.9	3.5	3.1	-	40	13	47			13	67	20	73	27	-
11.	3.7	3.5	1.5	7	67	13	13			-	53	47	67	27	6
12.	12.4	9.5	6.2	-	53	47	-			7	53	40	87	13	-
13.	10.5	8.1	7.7	-	33	40	27			13	47	40	73	27	-
14.	3.6	2.8	1.8	13	67	13	7			7	47	47	80	20	-
15.	10.1	9.1	6.0	-	60	33	7			7	53	40	40	60	-
16.	5.7	5.5	2.5	7	40	40	13			13	53	33	67	33	-
17.	7.2	7.4	4.0	20	73	7	-			-	60	40	60	40	-
18.	11.9	11.9	7.2	-	73	20	7			7	53	40	60	40	-
19.	7.9	7.5	6.7	-	60	27	13			7	47	47	47	53	-
20.	8.7	7.7	7.1	-	40	33	27			7	53	40	67	33	-
Total				9	47	27	17			7	60	30	63	36	1
1.	6.2	5.8	2.8	-	73	13	13			-	60	40	53	47	-
1.	6.3	5.7	4.1	-	93	7	-			7	27	67	53	47	-
2.	6.6	3.4	6.7	-	47	33	20			-	73	27	80	20	-

Table 2
Percentages of shape, roundness and sphericity of clasts in the Mulloch Hill Formation (locality 13)

2.2 GIRVAN SHORE

2.2.1 Craigskelly Conglomerate Formation

Table 1

	Maximum clast size			Shape				Roundness					Sphericity		
Unit	l	i	s	eq	tab	blad	rod	ang	suba	sr	r	wr	low	mod	high
3.	9.2	8.0	5.2	2	5	7	1				-	15	10	4	1
5.	12.6	12.3	11.8	5	6	3	1				-	15	5	8	2
7.	41.0	30.0	27.6	-	5	9	1				-	15	10	5	-
9.	15.0	11.0	6.0	-	7	8	-				-	15	8	7	-
10.	29.0	27.0	19.0	-	2	13	-				-	15	13	2	-
11.	8.2	7.1	4.4	-	7	8	-				-	15	8	7	-
13.	3.2	3.0	2.1	1	8	6	-				-	15	6	8	1
15.	22.0	17.0	13.0	-	3	10	2				5	10	12	3	-
17.	11.0	6.0	5.0	1	6	7	1				5	10	8	6	1
19.	3.6	2.7	2.0	-	6	7	2				4	11	9	6	-
21	2.8	2.7	1.9	-	7	6	2				2	13	8	7	-
Total	14.3			9	62	84	10				16	149	97	63	5

Table 1
Raw data collected from the Craigskelly Conglomerate Formation (Craigskelly, locality 204).

Table 2

	Maximum clast size			Shape				Roundness					Sphericity		
Unit %	l	i	s	eq	tab	blad	rod	ang	suba	sr	r	wr	low	mod	high
3.	9.2	8.0	5.2	13	33	47	7				-	100	67	26	7
5.	12.6	12.3	11.8	33	40	20	7				-	100	33	53	13
7.	41.0	30.0	27.0	-	33	60	7				-	100	67	33	-
9.	15.0	11.0	6.0	-	47	53	-				-	100	53	47	-
10.	29.0	27.0	19.0	-	13	87	-				-	100	87	13	-
11.	8.2	7.1	4.4	-	47	53	-				-	100	53	47	-
13.	3.2	3.0	2.1	7	53	40	-				-	100	40	53	7
15.	22.0	17.0	13.0	-	20	67	13				33	67	80	20	-
17.	11.0	6.0	5.0	7	40	47	7				33	67	53	40	7
19.	3.6	2.7	2.0	-	40	47	13				27	73	60	40	-
21.	2.8	2.7	1.9	-	47	40	13				13	87	53	47	-
Total	14.3			5	37	51	6				10	90	59	38	3

Table 2
Percentages of shape, roundness, and sphericity of clasts in the Craigskelly Conglomerate Formation

Table 1

	Maximum clast size			Shape				Roundness					Sphericity		
Unit	l	i	s	eq	tab	blad	rod	ang	suba	sr	r	wr	low	mod	high
217	14.5	12.0	10.0	-	12	16	2	15	11	4			18	12	-
223	28.2	3.4	3.3	1	13	5	8	13	15	2			16	13	1
Total	21.0			1	25	24	10	28	26	6			34	25	1

Table 1
Raw data collected from the Haven Conglomerates (localities 217-233), N = 100.

Table 2

	Maximum clast size			Shape				Roundness					Sphericity		
Unit %	l	i	s	eq	tab	blad	rod	ang	suba	sr	r	wr	low	mod	high
	14.5	12.0	10.0	-	40	53	7	50	37	13			60	40	-
	28.2	3.4	3.3	3	43	27	27	43	50	7			53	43	3
Total	21.0			1	42	40	17	47	43	10			53	42	2

Table 2
Percentages of shape, roundness and sphericity in the Haven Conglomerate.

Table 1

Unit	Maximum clast size l	i	s	Shape eq	tab	blad	rod	Roundness ang	suba	sr	r	wr	Sphericity low	mod	high
1a	3.3	1.7	1.5		4	7	4	5	6	3	1		11	4	
1b	0.7	0.5	0.2		6	4	5	7	3	5	-		9	6	
1c	8.1	5.1	5.6		6	6	3	3	3	9	-		9	6	
2	11.1	2.2	2.1		4	7	4	1	4	10	-		11	4	
Total	5.8				20	24	16	16	16	27	1		40	20	

Table 1
Raw data collected from the Scart Formation, locality 225. N = 60.

Table 2

Unit %	Maximum clast size l	i	s	Shape eq	tab	blad	rod	Roundness ang	suba	sr	r	wr	Sphericity low	mod	high
1a	3.3	1.7	1.5		27	47	27	33	40	20	7		73	27	-
1b	0.7	0.5	0.2		40	27	33	47	20	33	-		60	40	-
1c	8.1	5.1	5.6		40	40	20	20	20	60	-		60	40	-
2	11.1	2.2	2.1		27	47	27	7	27	67	-		73	27	-
Total	5.8				33	40	27	27	45	2			67	33	-

Table 2
Percentages of shape, roundness and sphericity in the Scart Formation.

2.3 POINT COUNTS FOR THE FORMATIONS IN THE CRAIGHEAD INLIER

2.3.1

Table 1

Formation	Mulloch Hill (11a)	Mulloch Hill (17c)	Newlands Cong. GC1a	Glenwells Burn 1	Glenwells Burn 2 (GB6)	Saugh Hill (SH1)
Quartz	57	23	34	40	31	28
Rock Fragments	135	181	177	149	100	199
Feldspar	8	4	-	4	-	-
Oxide	25	14	1	7	23	4
Quartz cement	7	0	20	-	1	6
Mica	4	16	-	12	16	25
Clay	64	56	68	70	129	38
Calcite cement	-	-	-	18	-	-
Porosity	-	-	-	-	-	-
Olivine	2	6	-	-	-	-

Table 1
Raw data from point counts of coarse-grained sandstones in the Craighead Inlier. N = 300 for each Formation.

POINT COUNTS FOR THE FORMATIONS ON THE GIRVAN SHORE

Table 2

	Craigskelly Conglomerate (CS9)	Woodland Formation Breccia (WF28)	Haven Conglomerate (QC2)	Scart Sandstone (SG32)
Quartz	37	13	38	34
Rock Fragments	170	78	194	159
Feldspar	5	-	-	3
Oxide	1	-	-	3
Quartz cement	6	-	1	-0
Mica	16	7	6	22
Clay	53	92	22	25
Calcite cement	12	110	39	54
Porosity	-	-	-	-
Olivine	-	-	-	-

Table 2
Raw data from point counts of coarse-grained sandstones, Girvan Shore. N = 300 for each Formation.

APPENDIX 3

3 RAW PALAEONTOLOGICAL DATA

3.1 CRAIGHEAD

3.1.1 Occurrence of Gastropods in the Mulloch Hill Formation

Table 1

Genus	Locality 19 + 74	32	41	81	Total
Loxoplocus (L) sedgwickii	1	1	-	4	6
L. (L) species	-	7	2	10	19
Phanerotrema sp.	-	-	-	1	1
Loxonema sp.	-	5	-	9	14
Murichisonia sp.	-	-	1	1	2
Kohenospira sp.	1	-	-	1	2
Liospara marklandensis	-	-	-	1	1
indet	-	2	1	2	5
Total	1	16	4	29	50

Table 1
Raw data documenting the gastropods in the Mulloch Hill Formation.
N = 50.

Table 2

Genus	Locality 19 + 74	32	41	81	Total
Loxoplocus (L) sedgwickii	100	6	-	14	12
L. (L) species	-	44	50	35	38
Phanerotrema sp.	-	-	-	3	2
Loxonema sp.	-	31	-	31	28
Murichisonia sp.	-	-	25	3	4
Kohenospira sp.	1	6	-	3	4
Liospara marklandensis	-	-	-	3	2
indet	-	13	25	7	10

Table 3

Genus	Locality 19 + 74	32	41	81	Total
Trachiform pleurotmarianceans	1	8	2	15	26
High spired	-	5	1	10	16
Lenticular pleurotmariaceans	-	-	-	1	1
Total	1	13	3	26	43 N=43

Table 3
Raw data

Trachiform pleurotmarianceans	100	62	66	58	61
High spired	-	38	33	38	37
Lenticular pleurotmariaceans	-	-	-	4	2

Table 4
Percentages of

3.1.2 Data on the Fauna of the Mulloch Hill Formation

Table 1

Fossil horizon	Composition of fauna Brach	Coral	Crinoid	Total	Preservation of brachs. Articulated	Disarticulated
Unit 2						
f1	145	-	-	145	9	136
f2	32	1	-	32	1	31
f3	175	-	-	175	22	153
f4	35	3	-	35	4	31
f5	127	1	1	127	19	108
f6	89	3	-	89	12	77
Unit 5						
f1	838	10	19	838	76	762
f2	n.t.	-	-	n.t.		
Unit 7						
f1	n.t.	-	-	n.t.		
f2	27	-	-	27	1	26
f3	22	3	-	22	4	18
Total	1490	21	20		148	1342

Table 1
Raw data for the composition of the fauna and state of preservation of the brachiopods of the Mulloch Hill Formation, locality 44. N = 1531. n.t. = not traceable.

Table 2

Fossil horizon	Composition of fauna Brach	Coral	Crinoid	Preservation of brachs. Articulated	Disarticulated
Unit 2					
f1	100	-	-	6	94
f2	93	3	-	3	97
f3	100	-	-	13	87
f4	92	8	-	11	89
f5	98	1	1	15	85
f6	97	3	-	14	86
Unit 5					
f1	97	1	3	9	91
f2	n.t.	-	-	-	-
Unit 7					
f1	n.t.	-	-	-	-
f2	100	-	-	4	96
f3	88	12	-	18	82
Total %	97	2	1	10	90

Table 2
Percentage of composition of the fauna and state of preservation of the brachiopods from the Mulloch Hill Formation (locality 44)

Table 3

Fossil horizon	Orientation of the brachiopods				Fragment
Unit 2					
f1	52	40	12	15	17
f2	15	7	4	4	1
f3	53	45	20	22	13
f4	13	8	3	-	7
f5	30	29	13	19	17
f6	24	20	17	13	3
Unit 5					
f1	280	168	99	110	105
f2	-	-	-	-	-
Unit 7					
f1	16	5	4	-	1
f2	7	2	1	5	3
f3	-	-	-	-	-

Total of disarticulated brachiopods 1342
Total of fragmented brachiopods 167
Total 1509

Table 3
Raw data for orientation of disarticulated brachiopods from the Mulloch Hill Formation (locality 44). N = 1509.

Table 4

Fossil horizon	Orientation of the brachiopods				Fragment
Unit 2					
f1	38	29	9	11	13
f2	48	23	13	13	3
f3	35	29	13	14	9
f4	42	26	10	-	22
f5	28	27	12	17	16
f6	31	26	22	17	4
Unit 5					
f1	37	22	13	14	14
f2	-	-	-	-	-
Unit 7					
f1	62	19	15	-	4
f2	39	11	5	28	17
f3	-	-	-	-	-

Total of disarticulated brachiopods 89%
Total of fragmented brachiopods 11%

Table 4
Percentages of the orientations of disarticulated brachiopods from the Mulloch Hill Formation (locality 44).

3.2 GIRVAN SHORE

3.2.1 Data on the fauna from the Woodland Formation (locality 232)

Table 1

Horizon	Composition of fauna Brach	Coral	Crinoid	Total	Preservation of brachs. Articulated	Disarticulated
(6)	47	-	-	47	1	46
13	147	-	-	147	3	144
14	20	-	-	20	-	20
20	54	-	-	54	-	54
22	15	-	-	15	-	15
26	46	-	-	46	-	46
28	139	-	-	139	1	138
29	137	-	-	137	-	137
30	7	-	-	7	-	7
	67	-	-	67	-	67
34	157	-	-	157	-	157
Misc	365	1	-	366	2	363
Total	1201	1	-	1202	7	1194

Table 1
Raw data on the composition of the fauna, and preservation of the brachiopods from the Woodland Formation (locality 232). N = 1202

Table 2

Horizon	Composition of fauna Brach	Coral	Crinoid	Total	Preservation of brachs. Articulated	Disarticulated
near base	100	-	-		2	98
13	100	-	-		2	98
14	100	-	-		-	100
20	100	-	-		-	100
22	100	-	-		-	100
26	100	-	-		-	100
28	100	-	-		1	99
29	100	-	-		-	100
30	100	-	-		-	100
3m above	100	-	-		-	100
Misc	99	1	-		1	99
Total	99	1	-		1	99

Table 2
Percentages of the composition of the fauna, and state of preservation of the brachiopods from the Woodland Formation (locality 232)

Table 3

Orientation of the brachiopods

Horizon						Fragment
near base	11	26	3	3	3	1
13	38	64	16	15	10	10
14	20	12	6	1	1	1
20	54	22	20	5	3	4
22	15	9	3	3	-	-
26	18	15	5	5	3	2
28	58	43	11	17	9	-
29	43	47	5	20	22	-
30	30	37		6	1	-
3m above	44	65	6	26	16	-
Misc	118	135	18	45	47	4
Total	404	461	73	141	115	19

Table 3
Raw data on the orientations of disarticulated brachiopods present in the Woodland Formation (locality 232) N = 1213.

Table 4

Orientation of the brachiopods

Horizon					
near base	24	56	6	7	7
13	27	45	11	10	7
14	60	30	5	5	-
20	41	37	9	6	7
22	60	20	20	-	-
26	39	33	11	11	6
28	42	31	8	12	7
29	31	34	4	15	16
30	41	50	-	8	1
3m above	28	41	4	17	10
Misc	31	34	4	15	16
Total %	34	39	6	12	9

Table 4
Percentages of orientations of disarticulated brachiopods present in the Woodland Formation (locality 232).

3.3 SAMPLE COUNTS

3.3.1 Sample Counts of the Brachiopod fauna in the Mulloch Hill Formation, Craighead Inlier

Table 1

	PV	BV	?	Broken	Artic	Total Valves	Total Inds	%
Mendacella mullockiensis (Davidson)	9	4	-	-	-	13	9	11
Eostropheodonta mullochensis (Reed)	-	1	1	-	-	2	2	2
Fardenia columbana (Reed)	1	2	-	-	-	3	2	2
Rostricellula mullochensis (Reed)	1	-	-	-	1	1	2	2
?Hyattidina angustifrons (Salter)	31	26	13	6	5	70	41	49
Zygospiraella scotica (Salter)	27	13	-	3	-	40	27	33
Indet	-	-	-	38	-	-	-	-
Total	69	46	14	47	6	129	83	-

Table 1
Sample count of brachiopod fauna from locality 19. The total number of valves is obtained by summing the number of pedicle valves, brachial valves and the number of indeterminate valves. The total number of individuals (inds.) is obtained by summing half the number of conjoined valves, half the number of indeterminate valves and the number of pedicle (PV) or brachial (BV) valves, whichever is the greater (after Harper). N = 182.

Table 2

Species	Unit 2	4	6	7	10
?Hyattidina angustifrons (Salter)	—	—	—	—	—
Zygospiraella scotica (Salter)	—	—	—	—	
Fardenia columbana (Reed)	—	—		—	
Mendacella mullockiensis (Davidson)	—	—			
Rostricellula mullochensis (Reed)	—	—			
Eostropheodonta mullochensis (Reed)		—			

Table 2
Distribution of brachiopods at locality 19.

Table 3

	PV	BV	?	Broken	Artic	Total Valves	Total Inds	%
Mendacella mullockiensis (Davidson)	-	2	-	-	-	2	2	10
?Hyattidina angustifrons (Salter)	4	12	-	-	6	16	15	71
Zygospiraella scotica (Salter)	3	1	-	1	-	4	3	14
Indet	-	-	2	-	-	-	1	5
Total	7	15	2	1	6	22	21	-

Table 3
Sample count of fauna from locality 74, N = 31.

Table 4

	PV	BV	?	Broken	Artic	Total Valves	Total Inds	%
Mendacella mullockiensis (Davidson)	27	34	-	2	-	61	34	20
Eostropheodonta mullochensis (Reed)	1	-	-	-	-	1	1	1
Fardenia columbana (Reed)	3	2	-	1	-	5	3	2
Rhynchotreta cuneata (Dalman)	-	-	1	-	-	1	1	1
Rostricellula mullochensis (Reed)	1	2	-	-	1	3	3	2
?Hyattidina angustifrons (Salter)	38	52	-	17	35	90	70	40
Zygospiraella scotica (Salter)	51	26	10	3	-	87	56	32
Indet	-	-	6	82	-	6	3	2
Total	121	116	17	105	36	254	171	-

Table 4
Sample count of fauna from locality 32, N = 395.

Table 5

	PV	BV	?	Broken	Artic	Total Valves	Total Inds	%
Pectrocrania mullochensis (Reed)	-	2	-	-	-	2	2	2
Mendacella mullockiensis (Davidson)	18	15	-	-	-	33	18	19
Eostropheodonta mullochensis (Reed)	-	-	1	-	-	1	1	1
Fardenia columbana (Reed)	2	3	-	-	-	5	3	3
Rhynchotreta cuneata (Dalman)	-	-	1	-	-	1	1	1
Rostricellula mullochensis (Reed)	1	2	-	-	1	3	3	3
?Hyattidina angustifrons (Salter)	32	24	8	7	29	64	51	54
Zygospiraella scotica (Salter)	8	2	-	-	-	10	8	8
Indet	-	-	15	23	-	15	8	8
Total	61	48	24	30	30	134	95	

Table 5
Sample count of fauna from locality 81, Rough Neuk. N = 193.

Table 6

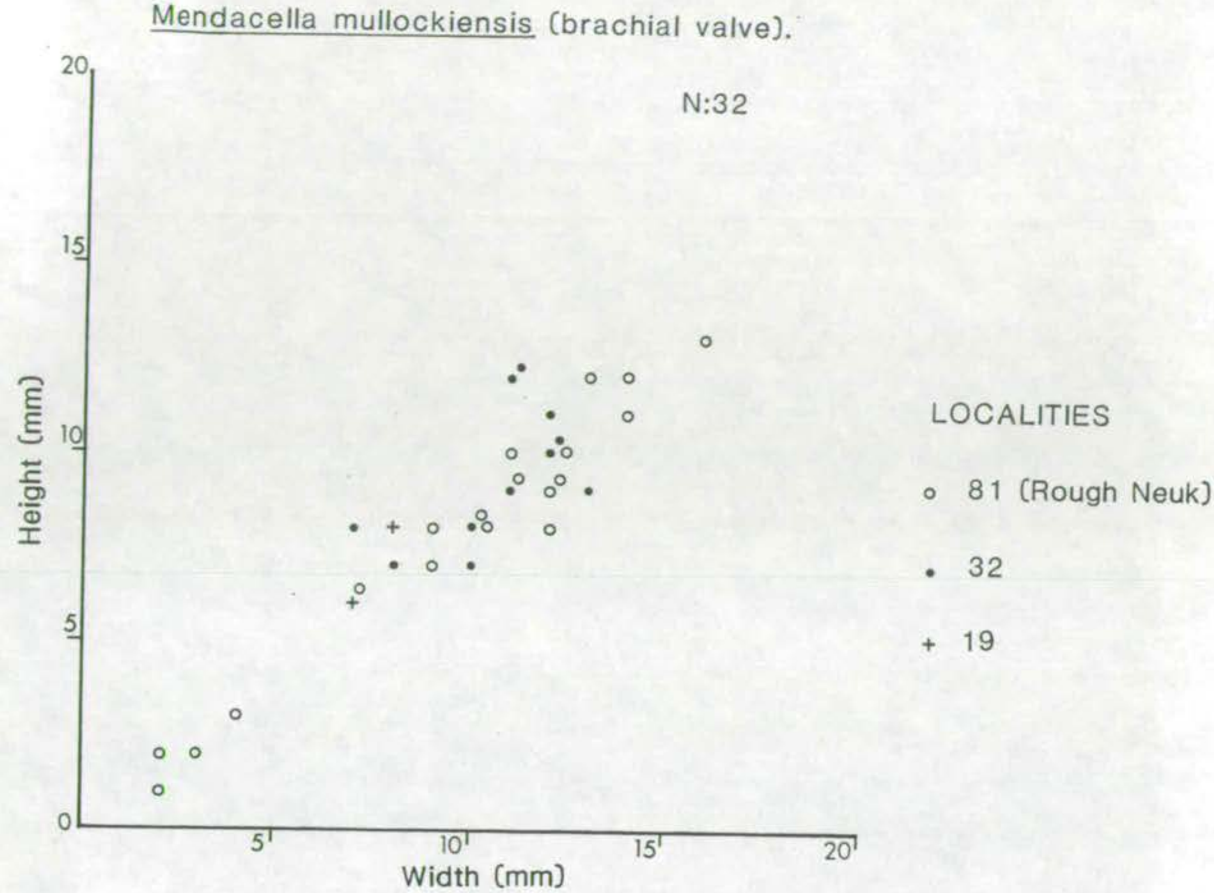
Preservation	Locality 19	74	32	81
Articulated	6	6	36	30
Disarticulated	129	22	254	134
Fragmented	47	1	105	30
Total	182	29	395	194

Table 6
Raw data on the state of preservation of the brachiopods in the Mulloch Hill Formation.

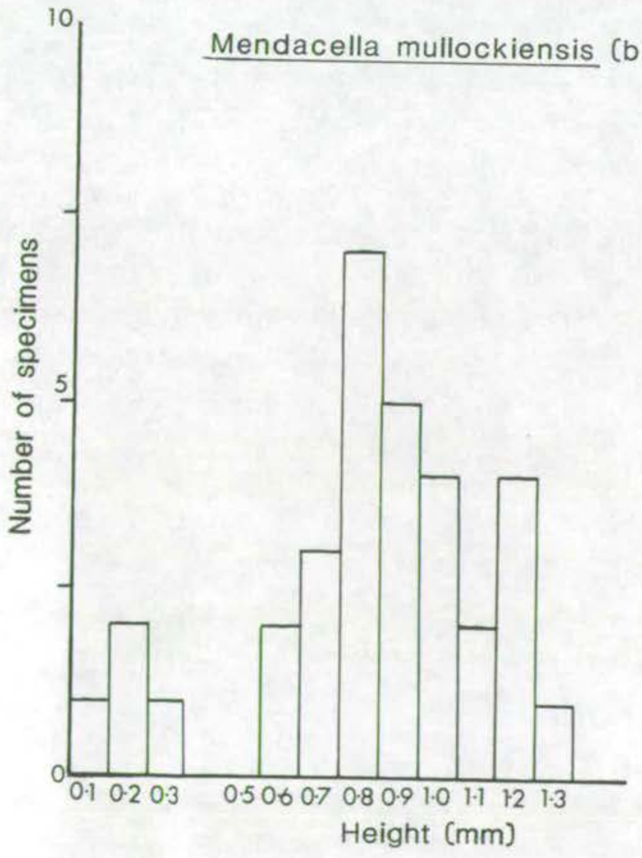
Table 7

Preservation	Locality 19	74	32	81
Articulated	3	21	9	19
Disarticulated	71	76	64	69
Fragmented	26	3	27	16

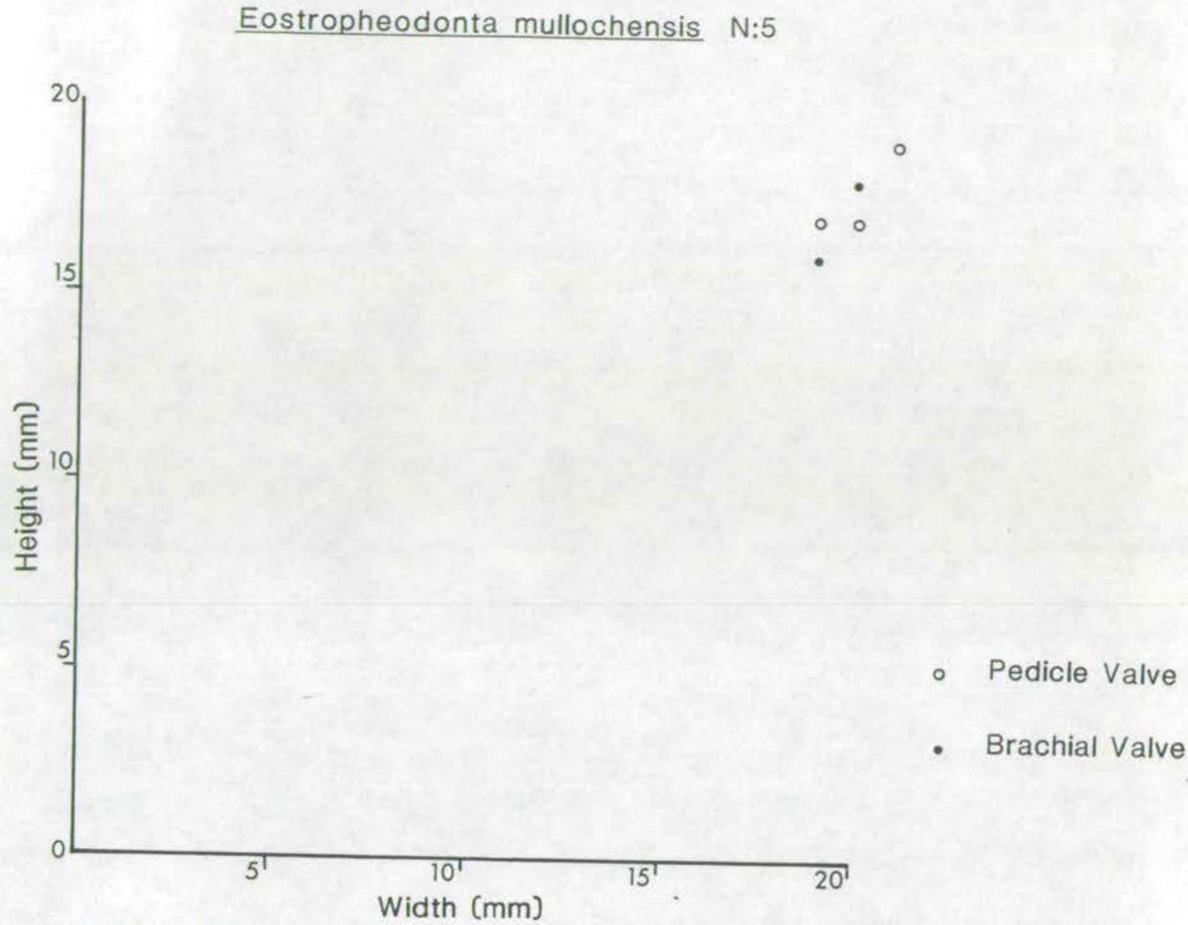
Table 7
Percentages of the state of preservation of the brachiopods in the Mulloch Hill Formation.



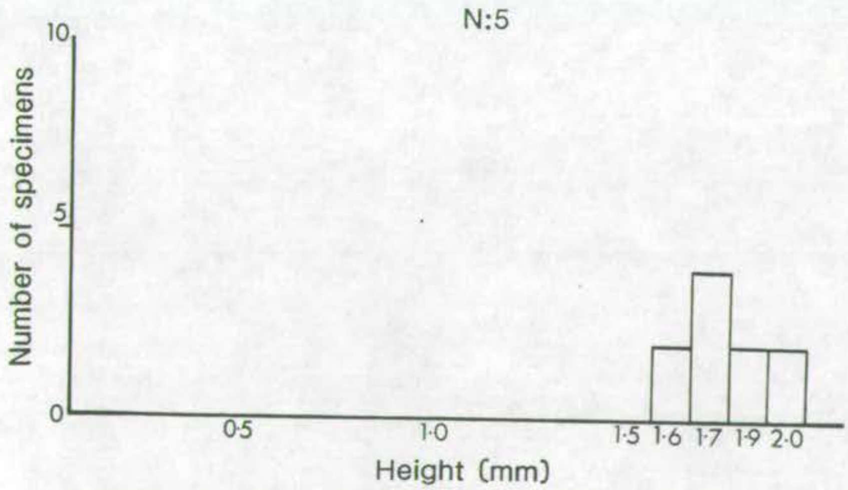
Fig(4.1.1) Size distribution of Mendacella mullockiensis (Davidson).



Fig(4.1.2) Size frequency distributions of Mendacella mullockiensis.

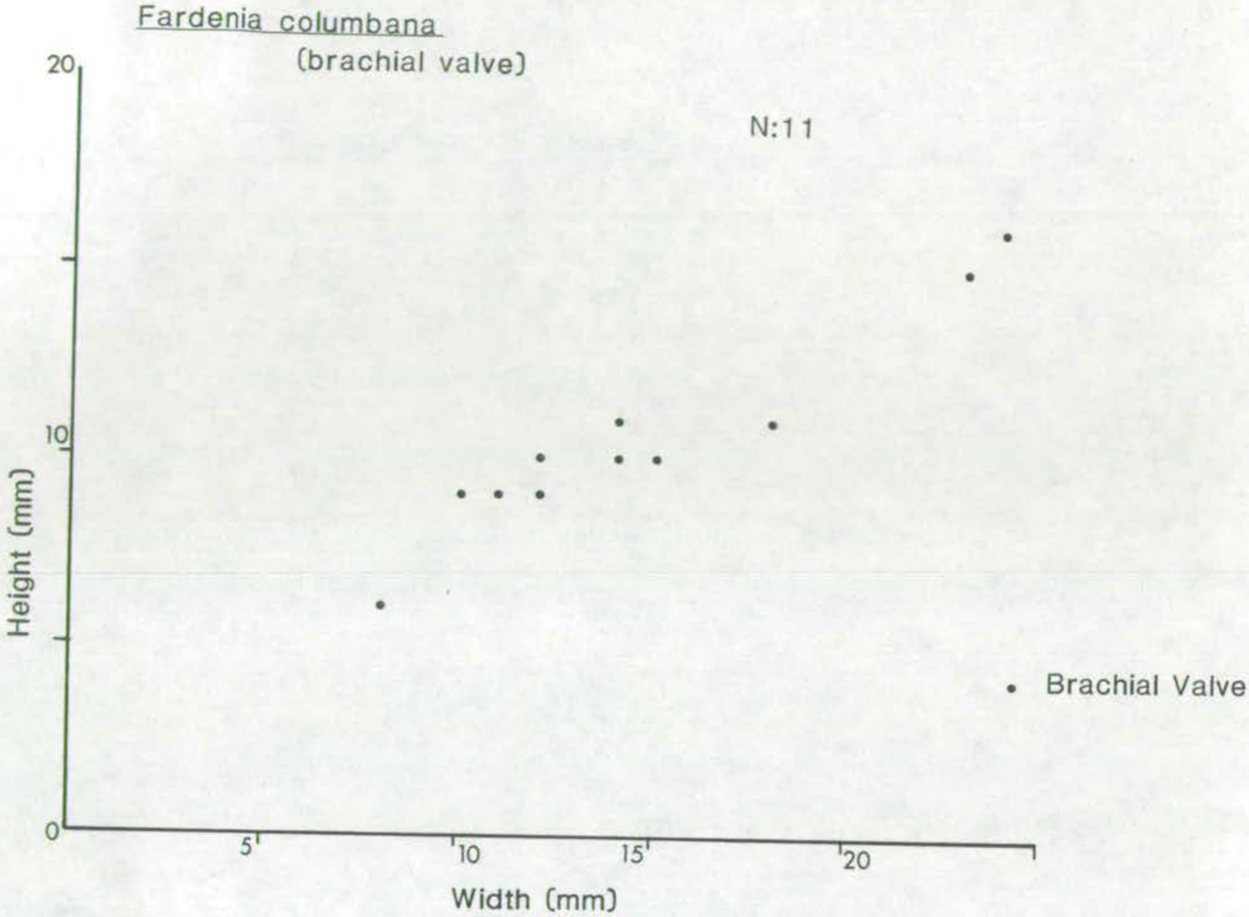


Fig(4.2.1) Size distribution of Eostropheodonta mullochensis (Reed).

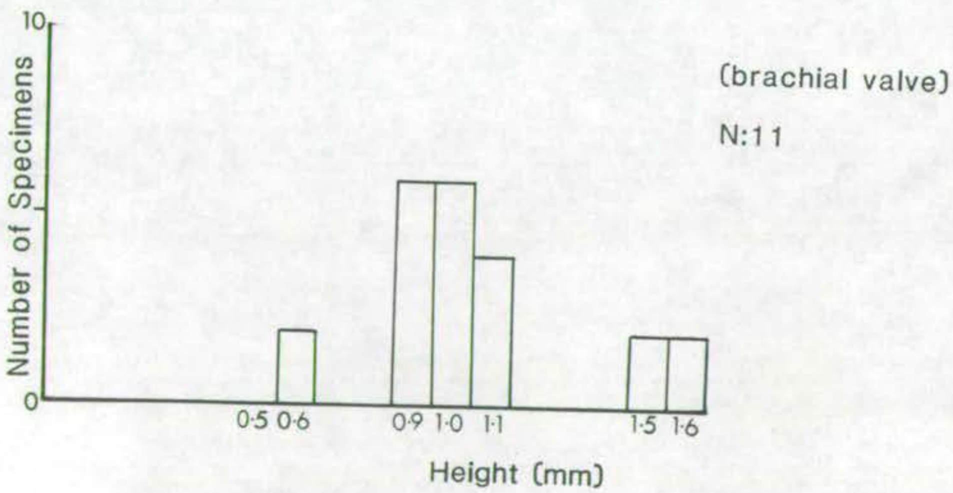


Fig(4.2.2) Size frequency distributions of Eostropheodonta mullochensis.

APPENDIX 4.3

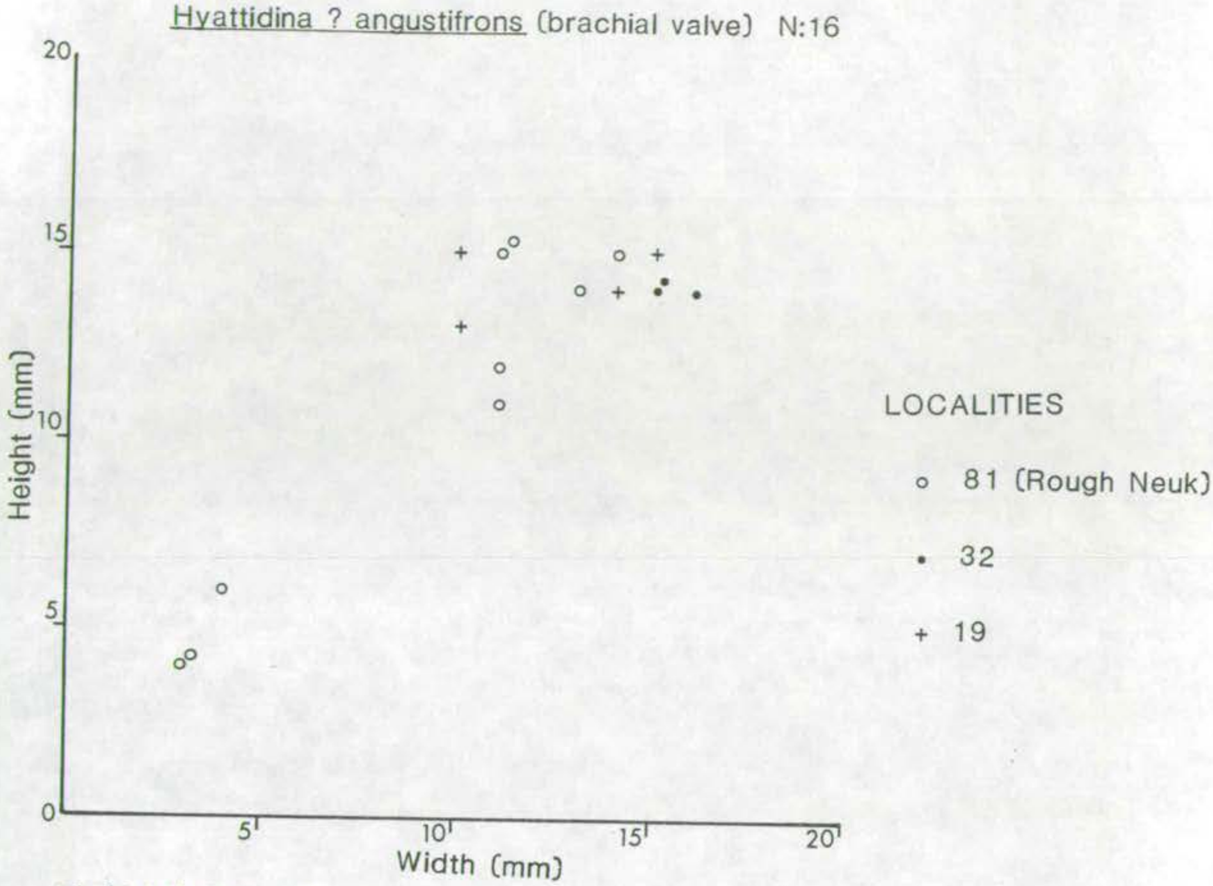


Fig(4.3.1) Size distribution of Fardenia columbana (Reed).

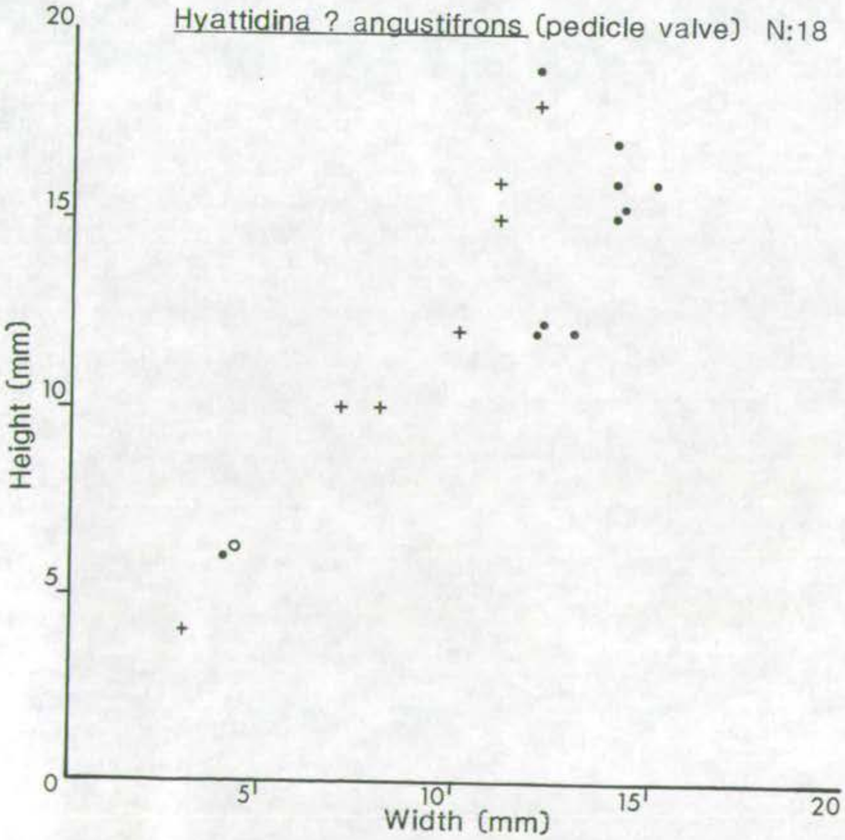


Fig(4.3.2) Size frequency distributions of Fardenia columbana.

APPENDIX 4.4



Fig(4.4.1) Size distribution of Hyattidina ? angustifrons (brachial valve).



Fig(4.4.2) Size distribution of Hyattidina ? angustifrons (pedicle valve).

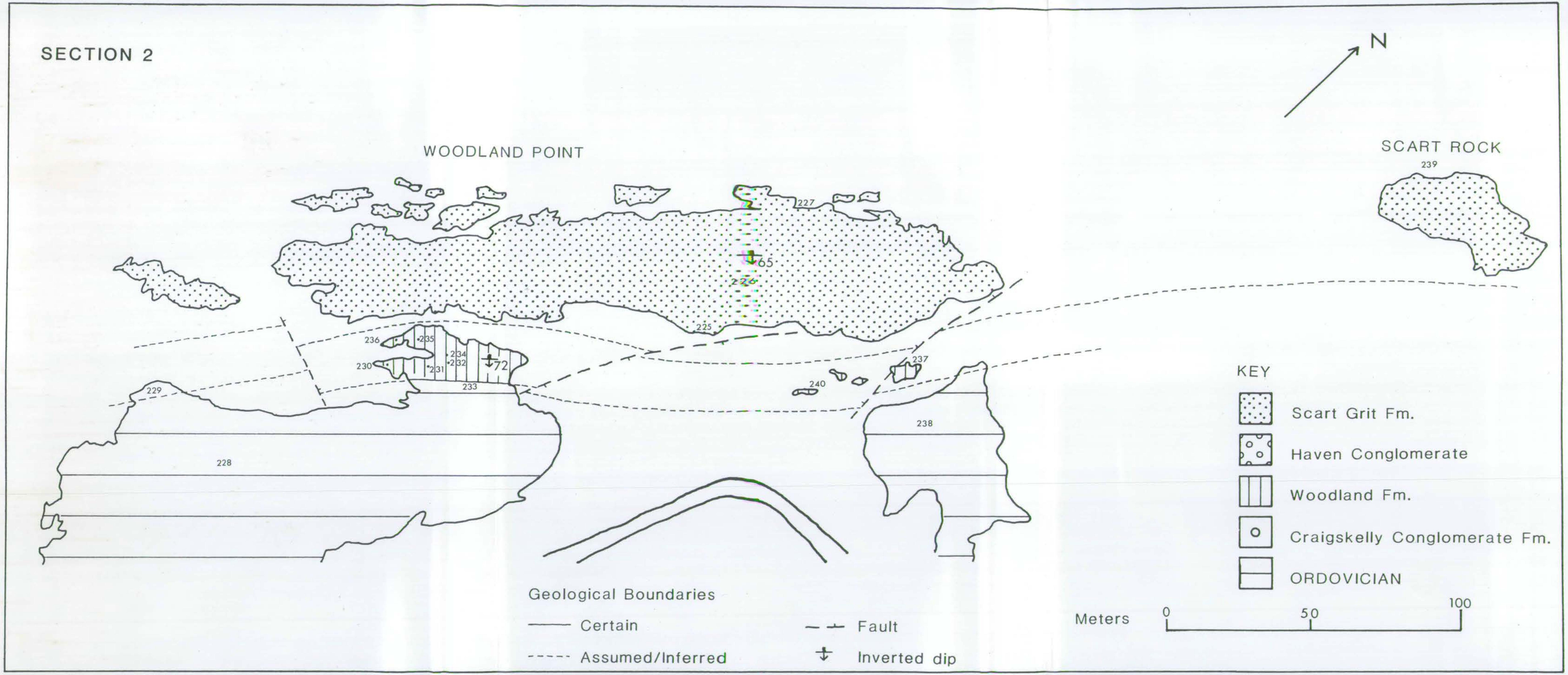
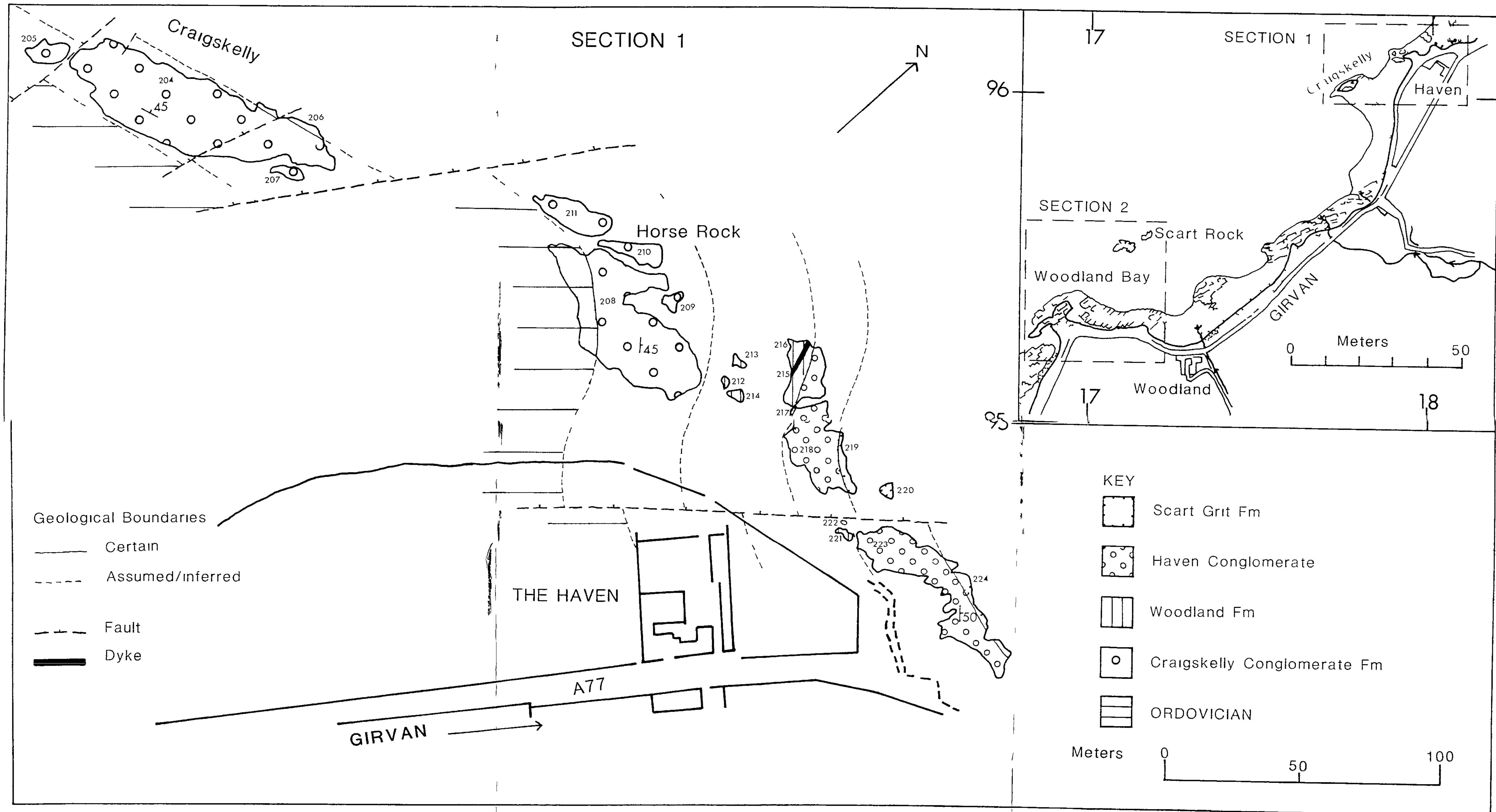

SECTION 2
N
WOODLAND POINT
SCART ROCK
239
227
65
226
225
236
235
234
232
231
230
72
233
229
228
237
240
238
KEY
Scart Grit Fm.
Haven Conglomerate
Woodland Fm.
Craigskelly Conglomerate Fm.
ORDOVICIAN
Geological Boundaries
Certain
Assumed/Inferred
Fault
Inverted dip
Meters
0
50
100

FIGURE 3.2



Fig(3 1) Geological map of The Haven (modified from Cocks and Toghill 1973)

FIGURE 3 1

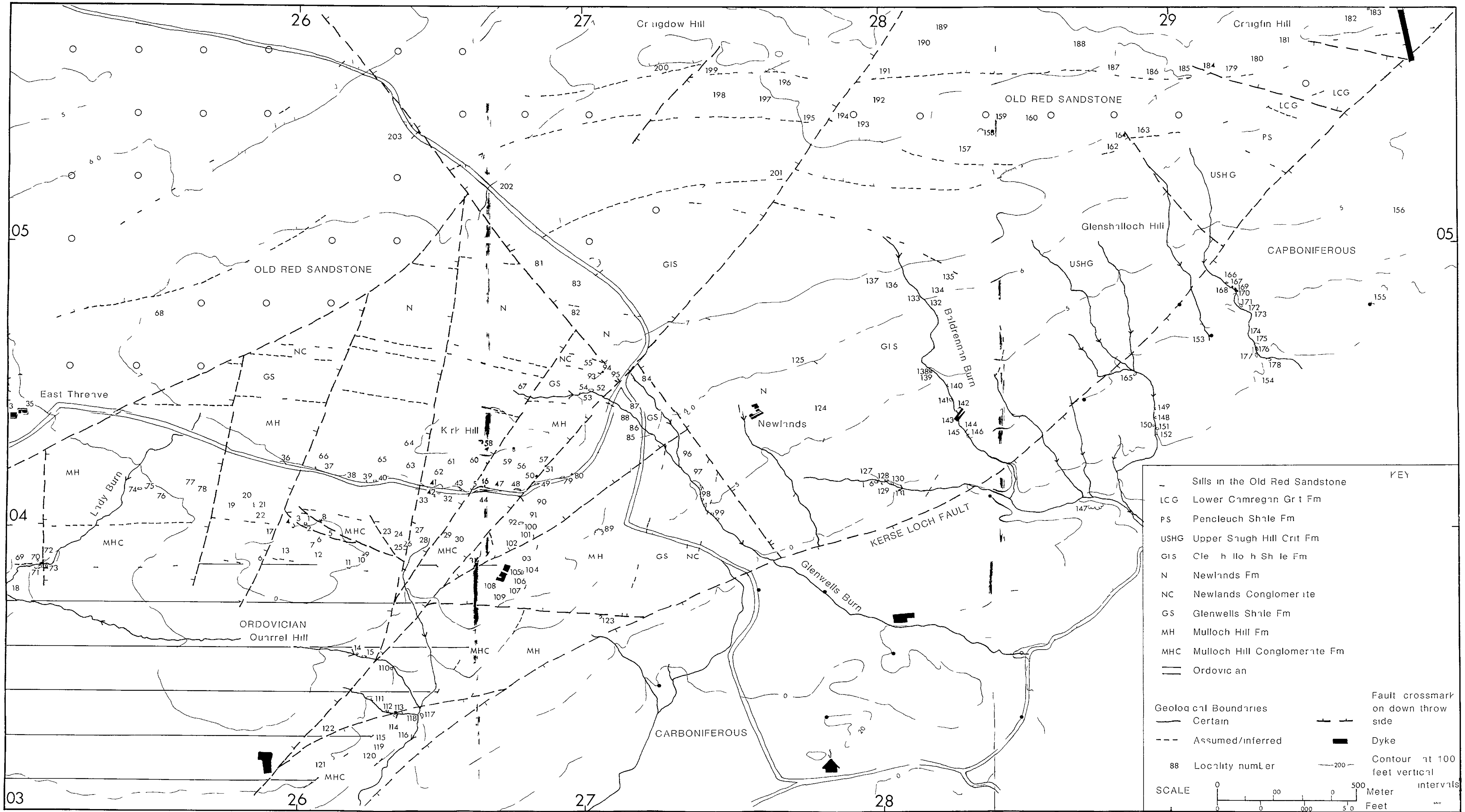


Fig (2 1) Geology map of the Craighead Inlier